INTERNATIONAL LASER RANGING SERVICE

2016–2019 REPORT

September 2020

Edited by C. Noll and M. Pearlman

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Preface

The 2016-2019 ILRS Technical Report is the seventh published volume for the International Laser Ranging Service (ILRS). This publication once again concentrates on achievements and work in progress rather than ILRS organizational elements. This latest edition of the ILRS report is structured as follows:

- Section 1 – Introduction examines the ILRS contribution to GGOS and the computation of the ITRF and its synergy with the other geodetic techniques.
- Section 2 – The Role of Laser Ranging details the SLR and LLR contributions to science and their role in other applications.
- Section 3 – About the ILRS, reviews the service, its mission, structure, and role in space geodesy.
- Section 4 – ILRS Operations, provides a report from the ILRS Central Bureau, summarizes developments at the ILRS Operations and Data Centers, and reviews website development, station performance reporting, and ILRS-related publications.
- Section 5 – Emerging Technologies, provides information on current trends in engineering and technology development within the ILRS and with the laser ranging technique
- Section 6 – Mission Support, provides an overview on ILRS support of satellite missions, reports from recent missions requesting ILRS support, and plans for the future.
- Section 7 –ILRS Analysis Activities, reviews the recent developments in ILRS analysis. This section includes individual summaries from ILRS Combination Center, Analysis, Associate Analysis, and Lunar Associate Analysis Centers.
- Section 8 – ILRS Network, provides the current status and recent performance statistics of the international stations supporting the ILRS and offers a perspective on site surveys and system co-locations. This section also includes contributed reports from stations in the ILRS network.
- Section 9 – Standing Committee, Study Group, and Board Reports, details the status of the ILRS Standing Committees, Study Groups, and Quality Control Board covering recent accomplishments and future plans.
- Section 10 – ILRS Meeting Summaries, reviews ILRS-related meetings in the 2016-2019 timeframe.
- Appendices – ILRS Information, lists organizations participating in the ILRS and defines acronyms used in this report.

This 2016-2019 ILRS Technical Report is also available through the ILRS website at URL *https://ilrs.gsfc.nasa.gov/about/reports/annualrpts/ilrsreport_2016.html.*

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Acknowledgment

The editors would like to acknowledge the essential contributions from our ILRS colleagues to this 2016-2019 edition of the ILRS Technical Report.

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Section 1:

Introduction

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Satellite Laser Ranging: An Essential Component of the Global Geodetic Observing System

The Global Geodetic Observing System (GGOS) of the International Association of Geodesy (IAG) provides the basis on which future advances in the geosciences can be built. By considering the Earth system as a whole (including the geosphere, hydrosphere, cryosphere, atmosphere and biosphere), monitoring Earth system components and their interactions by geodetic techniques and studying them from the geodetic point of view, the geodetic community provides the global geosciences community with a powerful tool consisting mainly of high-quality services, standards and references, and theoretical and observational innovations.

Satellite laser ranging is an essential part of the geodetic enterprise, for both monitoring the Earth system and for enabling geoscientific research. The solid Earth is subject to a wide variety of forces including external forces due to the gravitational attraction of the Sun, Moon, and planets, surficial forces due to the action of the atmosphere, oceans, and water stored on land, and internal forces due to earthquakes and tectonic motions, mantle convection, and coupling between the mantle and both the fluid outer core and the solid inner core. The solid Earth responds to these forces by displacing its mass, deforming its shape, and changing its rotation. Satellite laser ranging can measure the change in the Earth's gravity caused by mass displacement, the change in the Earth's shape, and the change in the Earth's rotation. Consequently, satellite laser ranging can be used to study both the mechanisms causing the Earth's shape, rotation, and gravity to change, as well as the response of the solid Earth to these forcing mechanisms. As a result, satellite laser ranging can be used to gain greater understanding of the Earth's interior structure and of the nature of the forcing mechanisms including their temporal evolution.

The availability of accurate, routine determinations of the Earth orientation parameters (EOPs) afforded by the launch of the LAser GEOdynamics Satellite (LAGEOS) on May 4, 1976, and the subsequent numerous studies of the laser ranges to LAGEOS, has led to a greater understanding of the causes of the observed changes in the Earth's orientation. LAGEOS observations of the EOPs now span more than 43 years, making it the longest available space-geodetic series of Earth orientation parameters. Such long duration homogenous series of accurate Earth orientation parameters are needed for studying long-period changes in the Earth's orientation, such as those caused by climate change. In addition, such long duration series are needed when combining Earth orientation measurements taken by different space-geodetic techniques. They provide the backbone to which shorter duration EOP series are attached, thereby ensuring homogeneity of the final combined series.

Radar altimetric observations of sea level rely on satellite laser ranging, as well as GNSS and DORIS, to provide the accurate orbits of the altimetric satellites that are needed for cm-level sea level determination. Gravimetric satellite missions like GRACE and GRACE-FO rely on satellite laser ranging to provide the longest wavelength components of the gravity field (degree-2 and degree-3 zonals). The present altimetric and gravimetric satellites can measure total sea level change and its mass component, both of which are vital for understanding global climate change. An important goal of GGOS is to integrate the measurement techniques that monitor Earth's time-variable surface geometry (including ocean and ice surfaces), gravity field, and rotation into a consistent system for measuring ocean surface topography, ocean currents, ocean mass, and ocean volume changes. This system depends on both globally coordinated ground-based networks of satellite tracking stations as well as on an uninterrupted series of satellite missions. The ground-based networks of geodetic stations also provide the measurements used to determine the terrestrial reference frame that is needed for studying regional and global sea level change and ocean-climate cycles like El Niño, the North Atlantic Oscillation, and the Pacific Decadal Oscillation. Much of the future progress in ocean observation will depend ultimately on the ability of the global geodetic community to maintain the accurate and long-term reference frame required for Earth observation.

Satellite laser ranging is therefore an essential component of the IAG’s Global Geodetic Observing System, providing critical satellite orbit observations, low-degree gravity field coefficients, Earth orientation parameters, and unique geocenter observations for the terrestrial reference frame. Continued improvements of these observations and contribution to the terrestrial reference frame will depend on technological innovation and adequate geographical coverage and co-location of SLR with the other geodetic measurement techniques of VLBI, GNSS, and DORIS. Implementing modern technology into a network of core geodetic sites with better geographic distribution and more uniform performance is a high priority of GGOS.

Richard Gross
Chair, Global Geodetic Observing System (GGOS)
Jet Propulsion Laboratory
September 11, 2019

Chairmans' Remarks

I was honored to serve as chairman of the Governing Board of the ILRS for three terms, from 2013 to 2018. During this period, I was delighted to see a growing demand of high accuracy SLR data, not only from our usual customers, but also from new ones. The space surveillance and tracking (SST) network needs our high precision distance measurement (either from cooperative and non-cooperative targets) to complement the "usual" direction information as well as less precise RADAR telemetry; on the other hand, the optical and quantum communication research work makes use of the advanced timing facilities embedded in a SLR station. Other than that, after more than 50 years of development, SLR remains unequaled as a fundamental technique for the definition of the Terrestrial Reference Frame.

Giuseppe Bianco
Agenzia Spaziale Italiana (ASI)
Matera, ITALY
Chairman, ILRS Governing Board (2013-2018)
August 2019

At the ILRS Governing Board Meeting held in Canberra in November 2018, I was elected as the new chairperson. Following the four predecessors, and as the first chairperson from Asia, I am thrilled to lead the ILRS. My term as chair is from January 2019 to December 2020.

We have successfully demonstrated our capability of yielding high-precision satellite tracking data since an early age, and it is truly exciting that more and more satellite providers are nowadays choosing to add laser reflectors on their missions. The number of ILRS targets is growing and has now reached nearly 100. On the other hand, the number of active laser tracking stations has been almost at the same level for a few decades. We need to strengthen the ILRS tracking network by increasing stations and/or making operations more efficient and thus contribute more to global-scale geodesy to its utmost precision.

The greatest assets of the ILRS are, in my view, challenging spirits and mutual stimulation. Having a variety of new applications of laser ranging technology/data, we should re-examine what we can potentially provide in the future and make our technical development more exciting. It will no doubt help attract more people from the outside and/or of a new generation.

I look forward to working with each institute and each individual member of the ILRS and also collaborating with related entities: other geodesy services, GGOS, IAG, and more.

Toshimichi Otsubo
Chairman, ILRS Governing Board (2019-2020)
Hitotsubashi University
Tokyo, JAPAN
August 2019

Section 2:

The Role of Laser Ranging

Section 2: The Role of Laser Ranging

Science from SLR

Author: *Frank Lemoine*
Responsible Agency: NASA Goddard Space Flight Center

In this section we review the science contributions of Satellite Laser Ranging (SLR) from 2016-2019. We discuss the highlights of results in different research areas from many papers that were published over this time. We have tried to synthesize the results, and provide a perspective on the most recent contributions of SLR to the terrestrial reference frame, altimeter satellite POD and the measurement of sea surface height, the measurement of mass change and time-variable gravity, GNSS, and the SLR contributions to fundamental physics.

ITRF2014

The leading science contribution of Satellite Laser Ranging (SLR) was its contribution to the different realizations of the International Terrestrial Reference Frame (ITRF) : ITRF2014 (Altamimi et al., 2016), DTRF2014 (Seitz et al., 2016 ; Bloßfeld et al., 2020), and JTRF2014 (Abbondanza et al., 2017). The SLR contribution was based on the processing of data from 1983 to 2014 (Luceri and Pavlis, 2017). Besides contribution of a time history of station positions, some from sites occupied since 1983, the SLR technique furnishes the origin of the TRF, and in combination with Very Long Baseline Interferometry (VLBI), the scale of the reference frame. The realizations of the Terrestrial Reference Frame (TRF) provide the fundamental reference for all geophysical observations of the Earth, particularly those pertaining to measurement of position, or the height of surfaces and how these positions and surfaces change with time.

The new ITRF solutions were evaluated for their performance on altimeter satellite precise orbit determination by Rudenko et al. (2017), Zelensky et al. (2018) and for their performance on SLR satellites by Rudenko et al. (2018). A general conclusion is that the impact on POD performance (measured via RMS of fit or RMS orbit differences) is smaller over the ITRF2008 data interval and larger over the ITRF2008 extrapolation period (2008-2014).

Improvements to ITRF2014

The SLR and GGOS analysis community worked intensively from 2016-2019 to improve the quality of the SLR technique and its contribution to the ITRF. The most significant result was presented by Appleby et al. (2016). The authors showed that station-dependent range errors from a variety of sources must be systematically accounted for in the weekly LAGEOS+LAGEOS-2 reference frame solutions. The authors showed that when this is done, the scale discrepancy between the SLR network and the VLBI network in ITRF2014 of about 1ppb is reduced by ~0.7 ppb. This led to detailed investigations by the ILRS Analysis Standing Committee (ASC) to systematically quantify the long-term biases on a station-by-station basis (Luceri et al., 2019). Finally, concomitant with these efforts, Rodríguez et al. (2019) developed improved Center-of-mass (CoM) corrections for the SLR geodetic satellites, derived from better modeling of the target response of these SLR targets. These improvements have been incorporated into the development of the SLR technique contribution to ITRF2020 and represent a major change from ITRF2014.

Another major improvement that will be incorporated into ITRF2020 will be the incorporation of time biases estimated from analysis of data to the Jason-2/Time Transfer by Laser Link (T2L2) experiment (Exertier et al., 2017). The T2L2 experiment showed that some stations exhibited time biases that changed with time, which for some stations reached up to several µsecs. The time biases were determined by using an orbiting clock (the DORIS Ultra-Stable Oscillator) to propagate time from a reference station (the Grasse SLR station equipped with a hydrogen maser) to the other ILRS stations that ranged to Jason-2. Ten years of these derived time bias corrections have been incorporated into the ILRS Data Handling File, which forms the basis of the data processing standards for analysis of SLR data to be included in ITRF2020 (*https://ilrs.dgfi.tum.de/fileadmin/data_handling/ILRS_Data_Handling_File.snx*). The challenge will be how to maintain time consistency with UTC for the SLR network, in the absence of an orbiting metrological reference, such as Jason-2/T2L2.

Visco and Lucchesi (2016; 2018) have worked to improve the modeling of the forces that perturb the orbits of LAGEOS, LAGEOS-2 and LARES spacecraft, with a focus on the thermal and magnetic forces. First, Visco and Lucchesi (2016) provide a critical review of the mass and moments of inertia for these satellites. The work clarifies inconsistencies and confusion that might exist in the literature regarding mass property information for the LAGEOS spacecraft. This mass property information is required in order to develop models of the evolution of the spin rate and spin axis orientation of the spacecraft. In the second paper, Visco and Lucchesi (2018) discuss the development of a new spin evolution model. While the author's motivation is to improve force modeling in order to obtain better measurements of the relativistic effects on the satellite orbits, the improved modeling could also benefit the estimation of geodetic parameters. Models of the spin axis orientation and spin rate enter into the calculations of these perturbative forces. So, in the future the work of these authors could be very useful for analysis of LAGEOS and LARES SLR data.

Hattori and Otsubo (2018) reached important conclusions concerning proper modeling of radiation forces on Ajisai. They showed that the solar radiation reflectivity coefficient, C_R, has a semiannual variation that can be attributed to the non-spherical cross-sectional area, and the low reflectivity of the surface material in the polar regions. They propose a model for analysts to use. It's important to note that Ajisai is a constituent in different solutions for the low-degree gravity field, so this effect, if unaccounted for, could alias into the time-variable gravity solutions.

In addition to the efforts to reduce systematic errors in SLR data, we note three papers that discussed simulations regarding emplacement of new stations, improvements in station performance due to better technology, and the importance of local ties.

Otsubo et al. (2016) simulated how new stations placed virtually around the globe would improve different geodetic parameters, including origin, scale, and the low degree terms of the gravity field. Based on their simulations, they find that, improvements of up to 20% are possible in the projected error for different parameters. Interestingly, stations on the Antarctic continent can reduce the error in the translation parameters, Tx and Ty, by up to 20%.

Kehm et al. (2018) in a different approach simulated improvements in performance of the current network, as well as the emplacement of up to eight SLR stations in new locations. A key point from their analysis is that the combination of increased performance (more observations) and better observation precision (improved data precision) can lead to significant improvements in the geodetic parameters. The authors find that the network performance improvement causes a decrease in the scatter of the network translation parameters of up to 24%, and up to 20% for the scale, whereas the technological improvement (improve in the quality of the observations) causes a reduction in the scatter of up to 27% for the translations and up to 49% for the scale. The results of these simulations reinforce the importance of modernizing the existing Legacy SLR network, and should encourage the operational and national agencies to pursue their efforts to update the technology of the existing stations.

Gläser et al. (2019) looked at the impact of injecting errors into site ties at key stations in a simulated GPS+SLR+VLBI TRF. The authors were able to identify which set of site ties by technique and by location had the most impact on the TRF. This study can be compared with the available library of site ties used for the ITRF (e.g., *http://itrf.ensg.ign.fr/local_surveys.php*), and inform decisions about where and when future local tie surveys can be conducted. The authors point out that the following SLR stations should have the best possible local tie standard deviations obtained from ground surveys: Fort Davis (McDonald Observatory), Monument Peak, Zimmerwald, Mount Stromlo, Graz, and Grasse.

Zajdel et al. (2019) looked at how to define the SLR datum for the reference frame. They found that some of the stations that are not included in the list of ILRS core sites could be taken into account as potential core stations in the TRF datum realization. They find that when using a robust station selection for the datum definition, the station coordinate repeatability can be improved by 4-8 % in the North, East and Up components

Altimeter Satellite Precise Orbit Determination

An important science contribution from SLR is in altimeter satellite precise orbit determination. In terms of tracking systems, the altimeter satellites fall into three categories: (1) the satellites using both SLR and DORIS: CryoSat-2, and SARAL. (2) the satellites that include SLR, DORIS, and GNSS: HY-2A, Jason-2, Jason-3, Sentinel-3A, Sentinel-3B, and (3) HY-2B, and ICESat-2 which use GNSS and SLR.

For CryoSat-2 and SARAL, the precise orbits are computed using a combination of SLR and DORIS data (e.g. Zelensky et al. (2016); Schrama (2018)). The CNES POD team uses the DORIS data as the primary data type but retains the SLR data as an external reference to evaluate precision and orbit stability (CNES, 2018). Since the altimeter orbit provides the reference for the science measurements, this means that the science results for these missions are directly traceable to the tracking data that have been used. SARAL is the first satellite to carry a Ka-Band altimeter, operating at 35.75 GHz (instead of 13.5 GHz for Jason-2). The Ka-Band altimeter provides a smaller footprint, better vertical resolution, and higher along-track sampling. The altimeter provided better observations of sea surface height over the oceans, better altimeter observations along the coasts and improved sampling of inland waters (lakes and rivers) (Verron et al., 2018). The CryoSat-2 mission has continued to gather data to support its main scientific goals: (1) to determine the regional and basin-scale trends in Arctic sea-ice thickness and mass; and (2) to determine the regional and total contributions to global sea level of the Antarctic and Greenland ice sheet (Parrinello et al., 2018). The CryoSat-2 altimeter also supplies data for oceanography and hydrology studies at global and regional scales (c.f. Bouffard et al., 2018).

SLR tracking, in combination with GNSS and DORIS has allowed the Jason-2 and Jason-3 satellites to continue the acquisition of altimeter data from the TOPEX reference ground track. The cumulative data from this series satellites (TOPEX through Jason-3) allows for the study of changes in the oceans along the same geodetic reference for up to 28 years. We can use ISI/Web of Science to gauge the scientific impact of these missions. According to ISI/Web of Science, from 2016 to 2019, 319 scientific papers were published that use Jason-2 and Jason-3 altimeter data. The most noteworthy products of these missions are the routinely updated estimate of the change in Global Mean Sea Level (GMSL) (Beckley et al., 2016), and the estimates of the acceleration in sea level rise (e.g., Nerem et al., 2018). The measurement of sea surface height to determine the change in GMSL is considered so societally important that the Ocean Surface Topography Science Team (OSTST) of the Jason-2+3 missions have determined that the missions need three independent means to track the spacecraft, which provide data at comparable levels of precision (OSTST, 2018). Only by intercomparing the GNSS vs. the SLR+DORIS orbits and showing that they agree at 6-8 mm radial RMS, and that the orbit comparisons are stable in time can we have confidence in the stability of the orbit reference for these missions and in the reliability of the measurement of sea level change.

The Sentinel-3A and Sentinel-3B missions were launched on February 16, 2016 and April 25, 2018 respectively. These missions carry multiple ocean-observing instruments, including a radar altimeter. The Sentinel satellites are sponsored jointly by the European Commission (EC) and the European Space Agency (ESA) under the aegis of the Copernicus program. For the radar altimeter, the objective is to collect altimeter data over the oceans (including coastal zones), rivers and lakes, and ice sheets (ESA, 2012). The satellites operate in high-inclination, sun-synchronous orbits, providing complementary spatial and temporal sampling to other altimeter satellite missions. The objective of the Copernicus program is to launch a series of missions for long-term environment monitoring (over more than 10 years). The requirement is for the orbits to be known at 1 cm radial RMS accuracy (Fernández et al., 2016). The POD requirement is met by using DORIS and GNSS as the primary tracking systems and using SLR data from a set of core stations of the ILRS to verify orbit performance and to rigorously intercompare the orbits produced by different analysis centers using different types of tracking data (Fernández et al., 2019).

The Haiyang-2 series of satellites (Haiyang, meaning ocean in Chinese), HY-2A, and HY-2B were launched on Aug. 16, 2011, and Oct. 25, 2018. The first SLR tracking data were acquired on Oct. 2, 2011 and Nov. 2, 2018 respectively. The satellites carry a DORIS and GNSS receiver in the case of HY-2A, and a GNSS receiver in the case of HY-2B. One of the payloads is a dual-frequency altimeter. The objective of the missions is to observe the oceans with various instruments and map the sea surface height. The spacecraft orbit the Earth at 971 and 973 km altitude from a 99.3 deg. inclination, sun-synchronous orbit. The orbit repeat periods used were 14-days during the mapping mission phase and 168-days during the geodetic mission phase. The HY-2A altimeter data are incorporated into the 25-year multi-mission sea level anomaly grids produced by the Data Unification and Altimeter Combination System (DUACS) in Toulouse, France. These multi-mission sea surface anomaly grids are distributed through the Copernicus Marine Environment Monitoring Service (CMEMS) (Taburet et al., 2019).

Time-Variable Gravity and Mass Change

It has been known for nearly 40 years that satellite laser ranging measurements of Earth orbiting satellites are sensitive to the time-variable gravity field of the Earth (e.g. Yoder et al., 1983, Guiterrez and Wilson, 1987). Over time researchers have used more satellites and better modeling to extract more time-variable coefficients and derive longer time series of data. Lemoine JM and Reinquin (2017), Cheng and Ries (2018), Meyer et al. (2019) provide recent examples of solutions obtained with SLR data alone or in combination with other data (either DORIS data from LEO satellites or GPS data from the Swarm satellites) where time series of low degree harmonics have been obtained. Using only the suite of SLR satellites, it is generally only possible to meaningfully resolve coefficients to about degree and order five on a biweekly or a monthly basis. Still the SLR-derived solutions can be used to resolve mass variations over Greenland, extending the time series of mass change to the early 1990's as shown by Talpe et al. (2017) and earlier by Matsuo et al. (2013).

An important application for SLR is by the GRACE and GRACE Follow-On missions. Since the start of the GRACE mission, the SLR-derived values are substituted for the GRACE values in the monthly solutions of each analysis center (e.g. see Loomis et al., 2019). The GRACE-derived values of C_{20} contain a non-geophysical signal arising possibly from a temperature-dependent error in the accelerometer data (Cheng and Ries, 2017). For the size of the anomalous C_{20} signal, look at Figure 1 of Cheng and Ries (2017). A time series of low-degree harmonics is derived using the exact same background modeling as that used by the GRACE solutions, and the SLR-derived values are substituted into the monthly GRACE solutions produced by the different GRACE analysis centers (University of Texas/CSR, GFZ, and JPL) (Cheng and Ries, 2018, Loomis et al., 2019). Whereas the K Band Range-rate data can resolve mass change down to spatial scales of a few hundred km, it is essential to model properly the broad mass-change signal associated with the oblateness term, C_{20}. Without the contribution of SLR, the mass change in Greenland from GRACE could not be properly resolved.

The GRACE satellites had a long operational lifetime, from launch in 2002 to the official end of the science mission in June 2017. However, due to degradation of the batteries, active thermal control was ended in April 2011. This meant two things: (1) that every 161 days (one solar beta-prime cycle) the K Band ranging instruments were shut off for 30-50 days; (2) the accelerometers were subject to temperature variations that complicated the analysis of the data (Klinger and Mayer-Gürr, 2016). After 2011 there were increasing gaps in the mission data products. Depending on how conservative a user feels regarding the GRACE mission data in this period, there is a gap of 2-4 years in the GRACE data products from 2014 to the launch of GRACE Follow-On in May 2018. The SLR data to the geodetic and other satellites provide a tool to "bridge the gap" in mass measurements between the missions of GRACE and GRACE Follow-On, both in SLR solutions alone, and in combination with other data such as the GNSS-kinematic orbits from the Swarm constellation (e.g. Meyer et al., 2019).

The GRACE Follow-On mission brought its own set of challenges. It emerged that one of the accelerometers on the GRACE-FO spacecraft produced spurious data. So the mission decided to use a method to "transplant" the accelerometer data from one GRACE-FO spacecraft to another (Bandikova et al., 2019). This approach seemed successful, however it became apparent that on GRACE FO both the C_{20} and C_{30} terms from the GRACE gravity solutions need to be replaced with the SLR-derived values. NASA GSFC provides a replacement product designated "GRACE Technical Note 14" based on processing to the SLR geodetic satellites (*https://podaac.jpl.nasa.gov/gravity/grace-documentation*).

The C_{30} coefficient has a large impact on the measurement of mass change in Antarctica. Fortuitously, (Loomis et al., 2020) point out that LARES being a member of the SLR geodetic satellite constellation is important for being able to reliably determine the C_{30} gravity harmonic from SLR data. The SLR-derived replacement values of C_{20} and C_{30} are also used for periods near the end of the GRACE mission when the twin spacecraft had only one functional accelerometer. In conclusion, the SLR data to the geodetic satellites are a vital part of the current system to measure mass change in the Earth system, and have helped both the GRACE mission and the GRACE FO mission to meet their prime mission requirements.

Geocenter

The geocenter is used to describe the orbital center of motion for all orbiting satellites. Geocenter motion represents the motion of the center of mass of the Earth with respect to its center of figure. Geocenter motion originates due to mass transport in the Earth system, e.g. processes involving atmospheric circulation, ocean mass transport and the hydrological cycle. Processes within the solid earth such as glacial isostatic adjustment (GIA) can also contribute. The geocenter motion or the degree 1 component of mass transport is not observable from a mission such as GRACE. Geophysical models predict the magnitude of geocenter motion on an annual scale to be 2-3 mm in X and Y and 4-5 mm in the Z direction. 1 mm of geocenter motion in X, Y, Z represents -0.5 mm, -0.26 mm and -0.62 mm of mean water thickness, respectively, over the oceans. Given that the present linear global change in mean sea level is presently about 3.3 mm/yr, failure to account for the degree 1 component of mass change would mean that scientists could not isolate properly the causes of sea level rise or close the sea level budget, without accounting for the degree one component of mass change. An error of 1 mm of geocenter motion in Z also represents about 69 gigatons of mass change in Antarctica, which is a sizeable fraction of the total amount of the current annual Antarctic mass loss of about 250 gigatons/yr (Wu et al., 2012, see Table 2-1; Rignot et al., 2019).

Different techniques can be used to infer geocenter motion on the temporal scales needed for mass change studies (see Wu et al., 2017 for an extended discussion). Presently the SLR technique can supply robustly geocenter solutions on an annual basis (e.g. see Ries et al., 2016, Riddell et al., 2017) based on LAGEOS and LAGEOS-2 data, although there are issues comparing the SLR-based solutions to other techniques because they are center-of-network and not center-of-figure. The LAGEOS-based geocenter solutions can possibly be improved by also using SLR data to other satellites such as GNSS or to LEO satellites, such as Sentinel-3 (Sośnica et al., 2019; Strugarek et al., 2019), or using the approach developed in JTRF2014 (Abbondanza et al., 2017). We should note that other satellite techniques can supply solutions for geocenter, either from DORIS or from GNSS (Männel and Rothacher, 2017; Couhert et al., 2018; Kang et al., 2019). Significant improvements to geocenter estimation using SLR data require reduction in the systematic errors (e.g. in biases or range delays at the stations and in modelling of target response at the satellite (Luceri et al. (2019); Rodríguez et al. (2019)), the deployment of new SLR systems, and a more balanced global network. Thus, the knowledge of geocenter in addition to being the foundation of the Terrestrial Reference Frame (TRF), is vital for monitoring of global mass change.

GNSS and SLR

GNSS realizes the Terrestrial Reference Frame (TRF) for users with a wide variety of civil and scientific applications. SLR has a direct connection to GNSS through the SLR retroreflectors on the satellites of the GNSS constellations (currently Beidou, Galileo, GLONASS, IRNSS and QZSS). Presently the ILRS tracking roster (*https://ilrs.gsfc.nasa.gov/missions/satellite_missions/current_missions/index.html*) includes 9 Beidou satellites, 28 Galileo satellites, 23 GLONASS satellites, 7 IRNSS satellites and 4 QZSS satellites. The SLR retroreflectors and the tracking provided by the ILRS provide a direct connection between the SLR and GNSS techniques which may be exploited for the possibility of colocation in space through combined processing of both observables for contribution to the ITRF (e.g. Thaller et al., 2015) or improvement in the strength and content of the SLR reference frame by improving station positioning and LOD (Length of Day) (e.g. Sośnica et al., 2018).

We discuss first the direct benefits of SLR tracking to the GNSS constellations, and then briefly review the role of SLR with GNSS orbit determination for LEO satellites. There has been an abundance of papers in the literature on these topics from 2016-2019, and those we cite below are meant only to provide examples of applications, not to cite an exhaustive list. A recurrent theme in many of the papers is the SLR validation of ambiguity-fixed GNSS orbits. Fixing ambiguities in GNSS precise orbit determination is an important advance in GNSS processing. The methodology of finding how to fix (i.e. to resolve) the majority of GNSS ambiguity biases in the analysis of GNSS data provides a way to improve GNSS orbit determination, by converting ambiguous ranges to non-ambiguous satellite ranges. A second major theme in the GNSS use of SLR data is the validation of improvements to solar radiation pressure modelling for satellites of the different GNSS constellations. A third theme concerns validation of new GNSS antenna offset coordinates or coordinates of the center-of-mass in the spacecraft frame. Ambiguities or errors in the definition of tracking point offsets or the center of mass can occur because of miscommunications, or errors in measurement of the reference points. They can be hard to sort out or confirm without simultaneously processing additional data for example SLR data to the GNSS satellites.

Orbit Validation

SLR data to GNSS satellites have been used to characterize different aspects of GNSS orbit determination performance: (1) to provide quality assessments for different types of IGS orbit products; (2) to characterize the relative performance of the different GNSS constellations; (3) to learn how different attitude modes or eclipse regimes might affect orbit quality; (4) to test implementation of ambiguity fixing in GNSS satellite POD. Examples of some papers that present these orbit validation results are listed in Table 2-1.

Table 2-1: Examples of SLR validation of GNSS orbit products (2016-2019)

Reference	Comment
Zajdel et al. (2017)	Online tool for validation of Multi-GNSS orbits.
Guo et al. (2017)	Analysis of orbit quality for 7 IGS Analysis Centers participating in the MGEX experiment (2012-2015).
Kazimierski et al. (2018)	Evaluation of real-time orbit products for multi-GNSS orbits.
Yang et al. (2019)	Analysis of Beidou orbits as part of the MGEX performance, including assessments by satellite, attitude mode and analysis center.
Katsigianni et al. (2019)	Validation of a technique to calculate Galileo satellite orbits with ambiguity fixing.

Improvement of Solar Radiation Pressure (SRP) Models

Rebischung et al. (2016) showed that the GNSS contribution for ITRF2014 contained the (solar) draconitic signal and its sub-harmonics are present in the geodetic products. For many years now, there have been efforts to improve the radiation pressure modeling for GNSS satellites. The large Area-to-mass ratios of the spacecraft (with the solar arrays) mean that radiation pressure has a big effect on the orbits. SLR data can be used directly to evaluate if the and to what extent the SRP models are improved. The approach can be to estimate parameters of a "box-wing" model, to test an improved empirical model such as ECOM2, or test an SRP model that has been developed using techniques that involve ray tracing. Some examples of the work done from 2016-2019 in this area are listed below:

Table 2-2: Examples of SLR Validation for GNSS SRP Models (2016-2019)

Reference	Comment
Rajaiah et al. (2017)	SRP Model for IRNSS satellites.
Darugna et al. (2018)	Test improved SRP model developed via ray-tracing for QZS-1
Bury et al. (2019)	Estimation of a box-wing (macro-)model for the Galileo satellites.
Duan et al. (2019)	Estimate macromodel (box-wing)-related parameters for Galileo, Beidou 2-3, QZS1-2.

Monitoring and Estimation of GNSS Offsets

Knowing the location of an antenna phase center in the spacecraft coordinate system and with respect to the satellite center of mass is an essential aspect of precise measurement modeling. For the GNSS satellites, new Phase Center offsets (PCOs) can be estimated, but then the question arises how one can verify the new estimates. SLR data as an independent measurement in this respect are a key method of evaluation as shown by Steigenberger et al (2016) for Galileo. In another example, Dach et al. (2019) were motivated to estimate new antenna offsets for some of the GLONASS satellites after noting a dramatic increase in SLR residuals. The estimated changes in the offsets were 5-15 cm. The authors attribute one possible explanation for the "sudden changes" in antenna offsets as a failure of a portion of the GNSS transmitter on the satellites. The true cause, however, remains unknown. Incidents of this point to the value of a continual monitoring of all the satellites in the GNSS constellations by SLR in order to spot these sorts of anomalies.

Antenna Thrust Impact on GNSS Orbits

The transmission of GNSS signals causes a radial "recoil" force on the satellite orbits that depends on the transmit power and the satellite mass. Steigenberger et al. (2018) found that the orbit radius could be reduced by -1 to -27 mm by the antenna thrust. The authors found it was difficult to verify with SLR data whether the model antenna thrust improved the SLR residuals, primarily because the effect might be masked by other sources of error, such as in radiation pressure modeling. Steigenberger et al. (2019) provide an update of the GPS and GLONASS satellite transmit power values from Steigenberger et al. (2018) as a basis for the 3rd reprocessing campaign of the International GNSS Service (IGS).

Validation of GNSS Orbit Determination for LEO Satellites

We have already discussed some aspects of GNSS orbit determination for altimeter satellites. Some other examples include:

1. Montenbruck et al. (2018a) who review kinematic GNSS and reduced-dynamic GNSS orbit determination for the Swarm satellites. The SLR data validate the implementation of ambiguity fixing for the kinematic orbits, where the standard deviation of the SLR residuals are reduced from 19.5-23.0 cm to 9.4-10.5 cm for the new orbits that they have calculated.
2. Hackel et al. (2018) who derive improved orbits for TerraSAR-X and TanDEM-X where the main improvements were application of a macromodel and use of ambiguity fixing. They obtain standard deviations in the SLR residuals of 11.4 and 12.5 mm respectively, an improvement of 33% over the earlier generation of precise orbits that had been made available.
3. Montenbruck et al. (2018b) who derive improved orbits for Sentinel-3A using ambiguity fixing. A novel result from their paper is that the new ambiguity fixed orbits reveal a potential 10 mm error in the cross-track location of the center-of-mass on the spacecraft. The SLR data confirm the improvements with the new orbits and also the sense of the error in the satellite center-of-mass.

Arnold et al. (2018) present an extensive general review of GNSS orbit determination for LEO satellites. It's worth reviewing some important conclusions from their paper which can perhaps encourage and inform improvements in SLR data quality and the deployment of new technologies to enable more precise (mm-level) SLR tracking of LEO targets.

1. SLR is a powerful tool for orbit validation.
2. To achieve the highest available orbit accuracy, models of the LRA range correction as a function of directional angles need to be applied. It is not adequate to apply a simple average value of the correction, as shown by Figure 3 in the Arnold et al. (2018) paper.
3. The SLR residuals to the GNSS orbits can be analyzed to estimate both range bias and station coordinate corrections to the a priori (SLRF2014) coordinate set. This analysis provides a method to provide quality control of station performance, and also to improve station coordinate estimation if LEO satellite SLR data from GNSS-track satellites can be incorporated into the SLR reference frame computation.
4. Since the GNSS orbits operationally achieve radial orbit accuracies of order 10 mm radial RMS, only a subset (12-15 stations) of the ILRS stations can provide fully useful information for GNSS POD orbit validation.
5. The technique of analyzing GNSS LEO satellite SLR residuals can also reveal large (µsec) level timing biases, which Arnold et al. (2018) show for Papeete (MOBLAS-8) for two epochs in 2016. This result demonstrates that processing of SLR residuals to GNSS precise orbits can identify large timing biases for SLR stations. The result also underscores the importance of SLR stations closely monitoring their equipment to make sure that they are coherent with UTC to within the prescribed ILRS requirements (+/- 100 ns).

In summary, SLR data provide a powerful tool for validation of the quality and accuracy of GNSS orbits computed for LEO satellites. This is quite an achievement, for many of these targets (e.g. Swarm, GRACE, TerraSAR-X and TanDEM-X) are at low altitudes and have very short passes. Tracking is only possible because the missions have routinely delivered accurate and timely (CPF) predictions for the stations. Nonetheless, to continue to advance, it is essential that the SLR technique continue to reduce systematic sources of error (e.g. range and timing biases). It is also essential that the ILRS community continue to deploy new SLR systems that enable mm-level satellite tracking.

Using SLR to Improve Models of GNSS Satellite Attitude

Steindorfer et al. (2019) discuss a ground and on-orbit test of ranging to a Galileo retroreflector array. The test, which was carried out with the kHz station at Graz (Austria), demonstrated it was possible to measure the orientation of the retroreflector array, and hence the orientation of the satellite, to an accuracy of 0.1° for specific station-satellite geometries. GNSS satellites mostly follow a yaw-steering algorithm, but this does depend on the satellite constellation (see Montenbruck et al., 2015). Special treatment of satellite attitude (e.g. for GLONASS, GPS and Galileo) is required during eclipse seasons and modeling the “noon” and “midnight” turns. So, this experiment demonstrates that with careful planning, campaigns of SLR measurements from kHz stations to GNSS satellites could be of tremendous value to the GNSS and geodetic community. Precise modeling of satellite orientation is required to model properly both the GNSS measurements in data analysis and to calculate properly the radiation pressure perturbations. What is not discussed in the paper, is whether solar array orientation could also be measured using kHz ranging. For the calculation of solar radiation pressure, misorienting a solar array even by a few degrees on a typical box-wing satellite (e.g. GNSS or Jason-2) can cause errors in the orbits and the geodetic products at the satellite draconitic period.

Thermospheric Mass Density

Atmospheric drag is the largest force acting on satellite orbits at low altitude. Atmospheric density at the spacecraft altitude strongly determines the magnitude of the drag force. The atmospheric density, itself varies with satellite altitude, latitude, solar time, and timing within the solar cycle. Solar indices and geomagnetic indexes are also drivers of atmospheric density (Emmert, 2015). The primary data for models of atmospheric density are : (1) density observations derived from satellite missions with precision accelerometers such as CHAMP, GRACE, and Swarm, (2) neutral mass spectrometer data ; and (3) satellite orbital ephemerides (Emmert, 2015). SLR data to geodetic satellites can sometimes be used as primary data to determine satellite orbits and then infer atmospheric density (e.g. Jeon et al., 2011), or as a tool to evaluate thermosphere density model performance (Warner and Lemm, 2016).

The geodetic or spherical satellites at low altitude are attractive targets for testing of thermosphere density models. Their spherical shape means the modeling of the nonconservative forces is simplified, compared to satellites with a complicated shape. Panzetta et al. (2018) used SLR data to the “Atmospheric Neutral Density Experiment-Pollux” (ANDE-P), developed by the Naval Research Laboratory, at 350 km altitude to evaluate four different atmospheric density models: CIRA86, NRLMSISE00, JB2008 and DTM2013. The SLR data were used to “calibrate” or adjust scale factors to the different models. Xiong et al. (2018) used SLR data to ANDE-Pollux to evaluate scale factors on another atmospheric density model, CH-Therm-2018, derived from CHAMP accelerometer measurements. In an interesting experiment with Starlette and Stella, but not using SLR data, Petit and Lemaître (2016) looked at the long-term evolution of the orbits of these satellites (1980-2012 for Starlette; 1994-2012 for Stella) determined from TLEs (two-line-elements) and compared the performance of three density models: DTM-2013, JB2008, and TD88. They were interested in how well each model “replicated” the observed satellite change in semimajor axis over several decades. Thus, SLR data and geodetic satellites are generally not a primary data source for derivation of thermospheric density models, but they play a useful role in thermospheric density model development.

Fundamental Physics

From 2016-2019, SLR also contributed to experiments that verified fundamental laws of physics, including the weak equivalence principle (Ciufoliini et al., 2019a), the Lense Thirring effect (Ciufolini et al., 2016; Lucchesi et al., 2019; Ciufolini et al., 2019b) and the measurement of the gravitational red shift (Delva et al., 2019).

The equivalence principle was first formulated by Galileo Galilei. In the context of general relativity, it means that two bodies with the same initial conditions follow the same geodesic of space time. Projected onto a spatial plane it would mean the test particles should follow the same ellipses (e.g. orbits). Tests are needed with objects with different mass properties over different distance scales to verify universality. The analysis of Ciufolini et al. (2019a) verified the weak equivalence principle to $2.0\ x\ 10^{-10} \pm 1.1\ x\ 10^{-9}$ over a range of 7890 to 12220 km using different materials (aluminum and brass for LAGEOS and LAGEOS-2, and sintered tungsten for LARES).

Einstein's General Theory of Relativity predicts that the orbital plane of a satellite is dragged by the rotation of massive body such as the Earth. J. Lense and H. Thirring derived the equations in 1918 (Lense and Thirring, 2018). We summarize the determinations from 2016-2019 in Table 2-1. The Lense-Thirring effect produces a precession of the node of 30.68 mas/yr for LAGEOS, 31.50 mas/yr for LAGEOS-2 and 118.50 mas/yr for LARES. The two most recent results verify the predictions of the Lense-Thirring effect to within two percent.

Table 2-3: Summary of Recent Tests (2016-2019) using SLR data to verify the Lense-Thirring effect.

Reference	Satellites used	Data Span	Results
Ciufolini et al. (2016)	LAGEOS, LAGEOS-2, LARES	~3.5 yrs	$\mu = 0.994 \pm 0.05$
Lucchesi et al. (2019)	LAGEOS, LAGEOS-2, LARES	L1,L2: ~25 yrs; LA: ~5.8 yrs	$\mu = 0.994 \pm 0.005$
Ciufolini et al. (2019b)	LAGEOS, LAGEOS-2, LARES	L1,L2: ~26 yrs; LA: ~7 yrs.	$\mu = 0.991 \pm 0.02$

The gravitational red shift refers to a consequence of Einstein's Theory of Relativity where clocks deeper in a gravitational field run slower than clocks further away. An opportunity arose to do a space test with two Galileo satellites (Galileo-201 and Galileo-202) that were accidentally launched into highly eccentric orbits. An elliptic orbit induces a periodic modulation of the relative frequency difference between a ground clock and the satellite clock. Using the accurate clocks (hydrogen masers) on these Galileo satellites for this "Galileo gravitational Redshift test with Eccentric sATellites" (GREAT) experiment (see *https://ilrs.gsfc.nasa.gov/missions/GREAT_exp.html* as well as Section 6 of this document), Delva et al. (2019) analyzed several years of Galileo tracking data, and were able to verify the relativistic predictions, and improve on the prior test done in 1976 with Gravity Probe A by a factor of 5.6, the first significant improvement in forty years. The SLR data played an essential role by helping to calibrate the radial orbit error for the GREAT experiment.

Science from LLR

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In 2019, Lunar Laser Ranging (LLR) celebrated its 50th anniversary. It continues the legacy of the Apollo period still enabling great science (Crease, 2019). In this section we briefly review the science contributions of LLR from 2016-2019, where normally always the full 50-year LLR dataset is analyzed. LLR has shown its strong capability to put Einstein's relativity theory to the test. In addition, lunar science and many quantities of the Earth-Moon dynamics could be studied, see Müller et al. (2019) for an overview.

Tests of General Relativity

The Earth-Moon system provides a unique laboratory to test General Relativity in the solar system. In the past years, LLR could strongly contribute to improve the limits for a number of relativistic parameters. Current improvements include, e.g., tests of the violation of Lorentz symmetry parameterized under the standard-model extension (SME) field theory framework (Bourgoin et al., 2016; Bourgoin et al., 2017). LLR analyses also provide constraints on the parametrized post-Newtonian (PPN) parameters (β and γ), and the geodetic precession of the lunar orbit (Hofmann and Müller, 2018). LLR puts the universality of free-fall to test (Viswanathan et al., 2018; Hofmann and Müller, 2018) and it was even used for recent tests of the equivalence principle for galaxy's dark matter (Zhang et al., 2020). Furthermore, LLR limits for the temporal variation of the gravitational constant (Hofmann and Müller, 2018) were used to further constrain some nominimally coupled dark energy and standard sirens (Tsujikawa, 2019). Summarizing, LLR analyses did not find any hints for a deviation from Einstein's theory of general relativity, but confirmed its validity impressively.

Lunar Science and Earth-Moon Dynamics

One further important part of LLR analyses comprises investigations of the physical properties and the interior of the Moon which can be studied via lunar tides, physical librations and the orbit (Williams and Boggs, 2015; Hofmann et al., 2018; Petrova et al., 2018; Viswanathan et al., 2019).

Discrepancies between LLR and GRAIL-derived results (Williams and Boggs, 2014; Williams et al., 2016) include, for example, elasticity parameters (Love numbers) and the degree-3 gravitational field, which leads room for further improvement, especially in the modelling of dissipation and further properties of the lunar interior.

Knowledge of the lunar fluid core's polar oblateness from LLR allows the estimation of the radius of the lunar core-mantle boundary and the lunar free-core nutation. It also helps to assess the hydrostatic nature at those depths (Viswanathan et al., 2019).

LLR analysis provides displacement Love numbers h_2 and l_2, the fluid-core/solid-mantle boundary (CMB) dissipation, and moment of inertia differences. Improved estimations of these parameters help constraining the long-term evolution of the Earth-Moon system (Williams and Boggs, 2016).

The tie between the ephemeris frame and ICRF, calculated from spacecraft VLBI (ΔDOR) data, is confirmed using the latest LLR data with an accuracy of 0.18 mas (3σ). LLR is potentially capable of tying the Earth–Moon system to ICRF (and hence, the whole ephemeris frame to ICRF) with an accuracy comparable to that of the ΔDOR-based tie (Pavlov, 2019).

Independent planetary and lunar ephemerides were generated using 50 years of LLR data at various institutions. Recent ephemeris versions are provided by Institut de mécanique céleste et de calcul des éphémérides (IMCCE) - INPOP19a (Fienga, 2019), by Jet Propulsion Laboratory (JPL) - DE430/431 (Folkner et al., 2014) and by Russian Academy of Sciences' (RAS) Institute of Applied Astronomy (IAA) - EMP2017 (Pitjeva and Pitjev, 2014; Pavlov et al., 2016). Model differences between independent solutions remain, but all solutions fit the past two decades of LLR data at the 1-2 cm (rms in one-way range) level.

Earth Rotation and Station Coordinates

LLR-based Earth orientation parameter (EOP) results contribute to combined EOP solutions, e.g., using JPL's Kalman Earth orientation filter (Ratcliff and Gross, 2018). Such combined solutions show a better fit to older LLR data than the IERS C04 series (Pavlov et al., 2016).

LLR also contributes to monitoring long-term variations of EOP (i.e., precession and nutation as well as Earth rotation and polar motion). For example, precession rate and nutation coefficients of different periods (18.6 and 9.3 years, 1 year, 182.6 and 13.6 days) have been determined and analyzed with respect to the values of the MHB2000 model of Mathews et al. (2002). Hofmann et al. (2018) obtained discrepancies to that nutation model of up to 1.46 mas.

Investigations on secular tidal changes in the lunar orbit and Earth rotation with larger data sets show improvements compared to older research (Williams and Boggs, 2016).

The coordinates of the ground observatories can be estimated with an accuracy between 0.4 and 3.6 cm and the velocities between 0.2 and 1.9 mm/yr. The comparison of the network geometry with the ITRF2014 reference solution shows 3-dimensional differences of up to 5 cm (Hofmann et al. 2018).

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Section 3:

About the ILRS

Section 3: About the ILRS

Author: *Carey Noll, Michael Pearlman*
Responsible Agency: ILRS Central Bureau

Mission of the ILRS

The International Laser Ranging Service (ILRS) organizes and coordinates Satellite Laser Ranging (SLR) and Lunar Laser Ranging (LLR) to support programs in geodetic, geophysical, and lunar research, as well as space science and engineering activities, and provides the International Earth Rotation and Reference Systems Service (IERS) with products important to the maintenance of an accurate International Terrestrial Reference Frame (ITRF). This reference frame provides the stability through which systematic measurements of the Earth can be made over thousands of kilometers, decades of time, and evolution of measurement technology. The Service provides precision ephemerides to support active Earth sensing missions and missions with optical receivers. The ILRS is one of the technique services of the International Association of Geodesy (IAG).

Role of the ILRS

The International Laser Ranging Service (ILRS):

- coordinates activities for the international network of SLR stations;
- develops the standards and specifications necessary for product consistency;
- develops the priorities and tracking strategies required to maximize network efficiency;
- collects, merges, analyzes, archives and distributes satellite and lunar laser ranging data to satisfy user needs;
- provides quality control and engineering diagnostics to the global network;
- works with new satellite missions in the design and building of retroreflector targets to maximize data quality and quantity;
- works with science programs to optimize data yield; and
- encourages the application of new technologies to enhance the quality, quantity, and cost effectiveness of its data products.

ILRS Organization

The ILRS organization, as shown in Figure 3-1, consists of the components required to address the goals of the service; the components include: Observing Stations, Operations Centers, Data Centers, Analysis Centers, a Central Bureau, and a Governing Board. Organizations participating in these components collaborate at all levels within the service to ensure efficient operations and consistent and timely delivery of data and derived products to a global user community.

- The Laser Tracking Network included of 43 SLR stations during the 2016-2019 period; providing ranging data on an hourly basis; four of these stations also provided Lunar Laser Ranging data;
- Two Operations Centers collected and verified the satellite data and provided the stations with sustaining engineering, communications links, and other support;

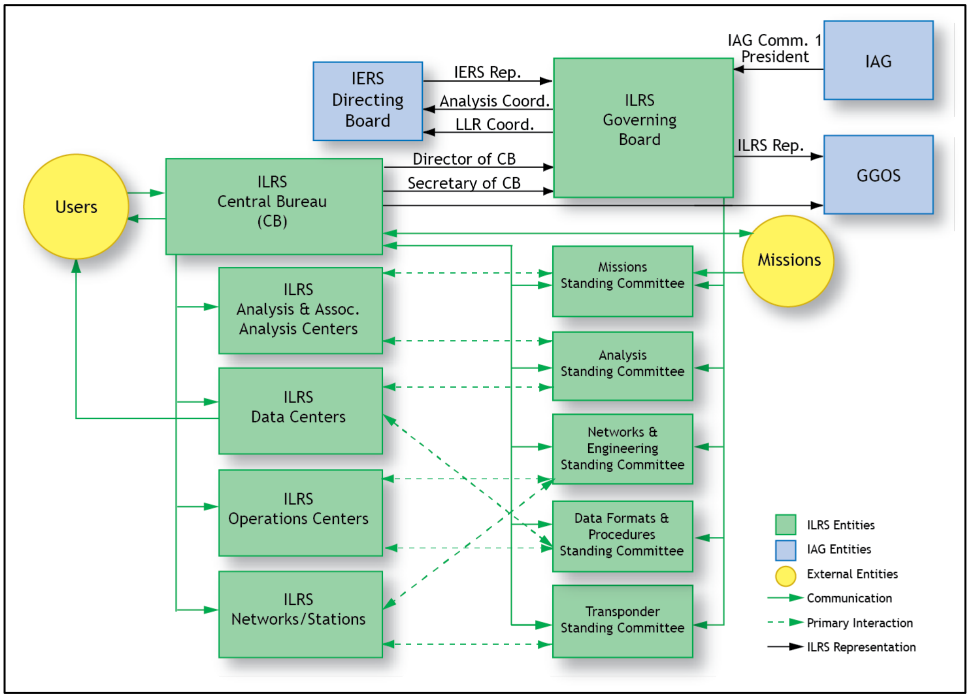
- Two Global Data Centers received and archived data and supporting information from the Operations Centers and provided these data to the Analysis Centers; and received and archived ILRS scientific data products from the Analysis Centers for availability to the user community;
- Two Combination Centers prepared the ILRS weekly data product, seven SLR Analysis Centers provided the input solutions to the Combination Centers for the data product process, twenty Associate Analysis Centers provided specialized SLR products to the users community and provided a second level of data quality assurance in the network; and six Lunar Analysis Centers provided lunar data products;
- Five ILRS Standing Committees (SCs) supplied technical expertise on special topics and areas and helped formulate ILRS policy; additional Study Groups (SGs) and Boards gave more focused attention on future ILRS activities or problem areas. The current Standing Committees, Study Groups, and Boards and their roles are:
  - Analysis SC – Developed, maintained, and coordinated the submission of the suite of standard ILRS products; provides feedback on the performance of the ILRS network.
  - Data Formats and Procedures SC – Developed, maintained, and reviewed standard procedures for generation and reporting of SLR data.
  - Missions SC – Reviewed and provided recommendations on applications submitted by missions requesting laser tracking and the priority for this support.
  - Networks and Engineering SC – Provided technical expertise in station performance analysis and coordinates engineering improvements across the global SLR network; communicated with both analysts and stations in data quality and quantity improvements.
  - Transponder SC – Provided advice, evaluation, and coordination on support of transponder and missions with in-orbit optical receivers for space geodesy and other scientific applications.
  - Space Debris SG – Served as an interface between the ILRS and agencies interested in space debris awareness as well as a forum to provide assistance, consultation, and help with hardware, software, and procedures to stations expanding their capabilities to use laser ranging for tracking space debris objects.
  - Quality Control Board – Addressed SLR systems biases and other data issues to help improve the quality of ILRS data and derived products.
- A Central Bureau provided the daily coordination and management of ILRS activities including communications and information transfer, monitoring and promoting compliance with ILRS network standards, monitoring network operations and quality assurance, determining satellite-tracking priorities, maintaining documentation and databases, and organizing meetings and workshops;
- A Governing Board supplied the general direction of the ILRS, defining official ILRS policy and products, developing standards and procedures, and interacting with other services and organizations.

Interactions with External Organizations

As shown in Figure 3-1, the ILRS cooperates extensively with other international organizations, serving on their governing bodies, etc.; current relationships include:

- International Association of Geodesy (IAG)
  - Representation on IAG Executive Committee
  - A representative from IAG Commission 1 serving on ILRS Governing Board

- International Earth Rotation and Reference Systems Service (IERS)
    - ILRS Technique Center Representatives on the IERS Directing Board
        - ILRS ASC Chair/AC Representative from ILRS Governing Board, and
        - Lunar Representative from ILRS Governing Board
    - A representative from IERS serving on the ILRS Governing Board
- Global Geodetic Observing System (GGOS)



- Network: 40+ stations
- Data Centers:
    - 2 Operations Centers
    - 2 Data Archive Centers
- Analysis Centers:
    - 7 Analysis Centers
    - 2 Combination Centers
    - 21 Associate Analysis Centers
    - 6 Lunar Analysis Centers
- Standing Committees: 5
- Central Bureau: 25+ members
- Governing Board: 18 members
- Membership
    - Associates: 400+
    - Organizations: 110+
    - Countries: 30+
    - Correspondents: 200+
- Supporting:
    - Users: 1000's
    - Missions: 110+

Figure 3-1. The components of the ILRS and their relationships with external groups.

Recent Updates to the ILRS Organization

The ILRS, like other services within the IAG, is guided by its Terms of Reference (ToR) which details the vision, objectives, structure, and operation, and specifies the data and products provided by the service to ensure consistency over time. In 2016, the ILRS Governing Board approved changes to its Terms of Reference to reflect changes in its organization and service activities. In particular, two additional At-Large members were added to the Board. At the direction of the IAG, working groups transitioned to standing committees; this change was also added to the ToR. Other updates included clarification of some processes and terminology in the document, updates to the Governing Board election process, and an update to the schedules for issuing official ILRS products. The updated ToR was approved by the ILRS Governing Board and accepted by the IAG in late 2016; the document is available on the ILRS website at: *https://ilrs.cddis.eosdis.nasa.gov/about/termsofref.html*

Governing Board elections are held every two years; recent elections were held to form the Board for the 2015-2016, 2017-2018, and 2019-2020 terms. During the 2017-2018 election, the Board was expanded to 18 members following the updates to the ToR. According to this new procedure, two additional members are nominated and elected by the ILRS Governing Board following its bi-annual elections. These new positions were added to the board to provide additional skills, organizational representation, geographic representation, or knowledge of use to the Board in carrying out its duties. The ILRS Governing Board membership during 2015-2019 is given in Table 3-1 below.

Table 3-1. ILRS Governing Board (2015-2020)

	**James Bennett** **Affiliation:** EOS Space Systems Pty. Ltd., Australia **Position:** WPLTN Network Representative (2016-2020)	**Carey Noll** **Affiliation:** NASA Goddard Space Flight Center, USA **Position:** Ex-Officio, Secretary, ILRS Central Bureau (2015-2020)	
	**Geoff Blewitt** **Affiliation:** University of Nevada, USA **Position:** Ex-Officio, Representative of IAG Commission 1 (2015-2016)	**Toshimichi Otsubo** **Affiliation:** Hitotsubashi University, Japan **Position:** WPLTN Network Representative (2015-2018) At-Large Representative Governing Board Chair (2019-2020)	
	**Giuseppe Bianco** **Affiliation:** Agenzia Spaciale Italiana (ASI), Italy **Position:** EUROLAS Network Representative (2015-2019) Governing Board Chair (2015-2018)	**Erricos Pavlis** **Affiliation:** Joint Center for Earth Systems Technology (JCET) and Goddard Space Flight Center (GSFC), USA **Position:** Analysis Center Representative (2015-2020)	
	**Ludwig Combrinck** **Affiliation:** Hartebeesthoek Radio Astronomy Observatory (HartRAO), South Africa **Position:** LLR Representative (2015-2016)	**Michael Pearlman** **Affiliation:** Harvard-Smithsonian Center for Astrophysics (CfA), USA **Position:** Ex-Officio, Director, ILRS Central Bureau (2015-2020)	

Table 3-1. ILRS Governing Board (2015-2020), continued

	**Urs Hugentobler** **Affiliation:** Technical University of Munich, Germany **Position:** Ex-Officio, Representative of IAG Commission 1 (2017-2020)	**Ulrich Schreiber** **Affiliation:** Technical University of Munich, Germany **Position:** At Large Representative (2015-2018) Appointed At-Large Representative (2019-2020)	
	**Georg Kirchner** **Affiliation:** Austrian Academy of Sciences, Austria **Position:** At Large Representative (2015-2019)	**Christian Schwatke** **Affiliation:** Deutsches Geodätisches Forschungsinstitut-Technische Universität München (DGFI-TUM), Germany **Position:** Data Center Representative (2017-2020)	
	**Vincencia Luceri** **Affiliation:** e-GEOS S.p.A., Italy **Position:** Analysis Center Representative (2015-2020)	**Andrey Sokolov** **Affiliation** RPC PSI, Russia **Position:** Governing Board Appointed At-Large Representative (2017-2018)	
	**David McCormick** **Affiliation:** NASA Goddard Space Flight Center, USA **Position:** NASA Network Representative (2015-2016)	**Krzysztof Sośnica** **Affiliation:** Inst. of Geodesy and Geoinformatics, Wroclaw University of Environmental and Life Sciences, Poland **Position:** Governing Board Appointed At-Large Representative (2019-2020)	

Table 3-1. ILRS Governing Board (2015-2020), continued

 **Jan McGarry** **Affiliation:** NASA Goddard Space Flight Center, USA **Position:** NASA Network Representative (2015-2019)	**Daniela Thaller** **Affiliation:** Bundesamt für Kartographie und Geodäsie (BKG), Germany **Position:** IERS Representative to ILRS (2015-2020) 
 **Stephen Merkowitz** **Affiliation:** NASA Goddard Space Flight Center, USA **Position:** NASA Network Representative (2017-2020)	**Jean-Marie Torre** **Affiliation:** Observatoire de la Côte d'Azur, Geoazur, France **Position:** LLR Representative (2018-2020) 
 **Jürgen Müller** **Affiliation:** U. of Hannover/Institut für Erdmessung (IFE), Germany **Position:** LLR Representative (2015-2018)	**Matthew Wilkinson** **Affiliation:** Natural Environment Research Council (NERC) Space Geodesy Facility (NSGF), UK **Position:** At-Large Representative (2017-2020) 
 **Horst Müller** **Affiliation:** Deutsches Geodätisches Forschungsinstitut-Technische Universität München (DGFI-TUM), Germany **Position:** Data Center Representative (2015-2016)	**Zhang Zhongping** **Affiliation:** Shanghai Astronomical Observatory (SHAO), China **Position:** Governing Board Appointed At-Large Representative (2017-2018) WPLTN Representative (2019-2020) 

Future Activities

Over the next two years we expect some of the SLR systems in process to come online, increasing the SLR geographic coverage (see Section 8). We also expect to see enhanced performance from systems now being updated. We will also try to work with some of the poorly performing stations to increase their productivity, with the realization that some may be operating under conditions with severe limitations.

In general, the legacy SLR systems are expensive to build, and in many cases, expensive to operate. The implementation of new technologies and automation is providing operational cost saving and enhanced capability. As new stations are fielded and current stations are upgraded and replaced, the cost of SLR operations should decrease. In general, the SLR community needs to examine further options for building less expensive systems that offer increased productivity.

With its new Quality Control Board (QCB) and other operational activities, the ILRS has made important strides in improving its data quality. We need to continue to stress this area in working toward reliable mm quality data products.

It would be advantageous for the ILRS to improve its connections with the other services and IAG entities. This past few years we worked closely with the IGS and ICG to develop a tracking strategy for GNSS that will better address the needs of a broad spectrum of users. In planning our first Laser Ranging School (held prior to the 2019 ILRS Technical Workshop in Stuttgart, Germany), we benefitted greatly from the IVS experience. We will continue to encourage ILRS members to connect with other services and ILRS entities and invite members of other such entities to a closer relationship with the ILRS.

Section 4:

ILRS Operations

Section 4: ILRS Operations

Author: *Carey Noll, Michael Pearlman*
Responsible Agency: ILRS Central Bureau

Overview

The International Laser Ranging Service (ILRS) organizes and coordinates Satellite Laser Ranging (SLR) and Lunar Laser Ranging (LLR) to support programs in geodetic, geophysical, and lunar research activities and provides the International Earth Rotation and Reference Systems Service (IERS) with products important to the maintenance of an accurate International Terrestrial Reference Frame (ITRF). This reference frame provides the stability through which systematic measurements of the Earth can be made over thousands of kilometers, decades of time, and evolution of measurement technology. The Service provides precision ephemerides to support active Earth sensing missions and now foresees support for extraterrestrial missions with optical transponders. The ILRS is one of the technique services of the International Association of Geodesy (IAG).

ILRS Central Bureau

The ILRS Central Bureau (CB) is responsible for the coordination and management of ILRS activities and for the communication with service components and the outside community. The CB establishes operating standards for its components and promotes compliance with these standards. The CB monitors network operations, coordinates satellite tracking, maintains the list of satellites tracked and their priorities, maintains the ILRS website and associated documentation, generates reports on data production and station data quality, and organizes workshops (both the bi-annual International Workshop on Laser Ranging and ILRS Technical/Specialty Workshops). The ILRS CB is managed by NASA Goddard Space Flight Center and meets typically every month to address current issues and monitor operations throughout the service.

The ILRS Central Bureau works with current missions to resolve any issues with SLR tracking support, both from the mission and ILRS standpoint. The CB also coordinates future mission support, accepting new Mission Support Request forms, coordinating approval of these forms through the Missions Standing Committee (MSC) and the Governing Board, and working with the mission to start ILRS tracking support.

Recent Developments

Mission Support

During 2016-2019, the ILRS CB assisted agencies to start new tracking support for 11 missions and three future missions. The CB also coordinated three intensive tracking campaigns. More information about the new mission support and tracking campaigns during the 2016-2019 time period can be found in Section 6 of this report.

Workshop Organization

The ILRS sponsors International Workshops on Laser Ranging (IWLRs) which are typically held every two years. In addition, the ILRS organizes focused technical or specialized workshops in years between the International Workshops on Laser Ranging. In September 2019, the ILRS Central Bureau published new guidelines interested parties should follow when proposing to host future workshops and for the ILRS infrastructure to use in planning these workshops. The guidelines have been published on the ILRS website at: *https://ilrs.gsfc.nasa.gov/about/reports/workshop/ILRS_Workshop_Guidelines.html*.

During 2016-2019, the ILRS Central Bureau assisted the Scientific and Local Organizing Committees for four workshops as shown in Table 4-1 below.

Table 4-1. List of ILRS Workshops, 2016-2019

Workshop and Theme	Dates and Location
20th International Workshop on Laser Ranging "The Path Toward the Next Generation Laser Ranging Network"	October 09-14, 2016 Potsdam, Germany
2017 ILRS Technical Workshop "Improving ILRS Performance to Meet Future GGOS Requirements"	October 02-06, 2017 Riga, Latvia
21st International Workshop on Laser Ranging "Laser Ranging for Sustainable Millimeter Geoscience"	November 05-09, 2018 Canberra, Australia
2019 ILRS Technical Workshop "Laser ranging: To improve economy, performance, and adoption for new applications"	October 21-25, 2019 Stuttgart, Germany

Summaries of these workshops can be found in Section 10 "ILRS Meeting Summaries" of this report.

Updates to Site Log Format and Processing

The ILRS site logs contain critical information for users about the configuration of SLR stations. The Data Formats and Procedures Standing Committee (DFPSC), the Networks and Engineering Standing Committee (NESC), and the ILRS CB developed an updated site log format to clarify and extend the content of several sections in the logs. In addition to the format updates, EDC staff developed web-based procedures for update and submitting site logs through their website. This new system provides an immediate format check for station managers when updating their site logs online. Valid site logs are then automatically submitted to the ILRS CB for final review and approval; once complete, the logs are made available at the CDDIS and EDC and integrated into the ILRS website.

Members of the ILRS CB assisted EDC staff in converting site logs to the new format and reviewing their final updates. Personnel worked with the stations to resolve questions and outstanding issues from the conversion. The new site log format and submission/processing procedures were finalized in 2019 and all current stations utilize the updated format to maintain their information.

Station Performance Assessment Reporting

In 2015, the ILRS updated the station performance standard to require stations to obtain a total of 3500 passes per year in order better realize the goals set by the ILRS and GGOS. ILRS Central Bureau personnel and CDDIS staff developed a new reporting system that generates monthly station performance assessment maps to help ILRS and individual stations improve our understanding of overall network performance and determine steps for improvement. The reports consist of a set of maps for each station that illustrate how the station adheres to the established ILRS system performance standards as well as summarizing tracking capabilities, interleaving, normal points per pass, and priority list compliance. The station-specific maps reflect data assessed over the previous twelve months in various categories:

- General (overall score, total passes, total normal points)
- Adherence to ILRS priority list
- Satellite support by category (e.g., number of passes, number of NPTs/pass, percentage of ILRS standard)
    - Altimetry
    - Geodetic
    - GNSS

The reports, and additional information about the assessment software, are accessible at URL: *https://ilrs.gsfc.nasa.gov/network/system_performance/monthly_station_performance_maps/index.html*.

ILRS Operations and Data Centers

Two ILRS Data Centers (DCs) support the user community by providing an archive of and access to laser ranging data, products, satellite predictions, and related information:

- Crustal Dynamics Data Information System (CDDIS), located at NASA Goddard Space Flight Center (GSFC), Greenbelt MD USA, *https://cddis.nasa.gov*
- EUROLAS Data Center (EDC), located at Deutsches Geodätisches Forschungsinstitut, Technische Universität München, Munich Germany, *http://edc.dgfi.tum.de/en/*

The EDC also serves as an ILRS operations center for receipt and quality control of laser ranging data from a subset of stations in the ILRS network; a NASA operations center provides this service primarily for stations in NASA's SLR network. These OCs exchange validated data on an hourly and a daily basis and then forward these data to the ILRS data centers for user access.

Laser Ranging Data

Laser ranging data consist of the round-trip time measurement (and epoch of measurement) from the ground station to retroreflectors on the satellite or on the surface of the Moon. These data will later be corrected for refraction delay and offset to the satellite center of mass in the case of satellites. ILRS stations routinely transmit two types of laser ranging data: full-rate data, which include all range observations obtained during a satellite's pass, and normal point data, where range observations are averaged over the pass, thus condensing the number of range observations reported for the pass. Users can utilize full-rate data for scientific applications as well as for engineering evaluation of the laser tracking systems and satellite targets. SLR normal points, however, are considered the principle ILRS data set. Stations create normal points by using algorithms to sample and aggregate the full-rate data over time. The altitude of the satellite primarily determines the length of this sampling interval, e.g., lower orbiting satellites use a shorter normal point interval than satellites in a higher orbit.

The CDDIS and EDC data centers provide SLR data files in three forms: hourly, daily, and monthly. Hourly and daily files contain all passes from all satellites received by the operations centers in the previous one-hour/24-hour time span respectively. The third type of normal point data file is a monthly, satellite-specific file that contains data for the particular month. Users then have alternate ways for accessing SLR data, all data received during an hour or day-time span, or all data with timestamps for a particular month.

Satellite Predictions

Stations in the ILRS network require predicted satellite ephemerides to track missions on the ILRS priority list. All satellites approved for tracking by the ILRS must have valid satellite predictions available at the ILRS data centers for access by the stations. For tracking satellites with no restrictions, stations obtain orbit predictions through e-mail or by downloading files from the ILRS data centers. Satellites missions with restricted tracking requirements must provide predictions directly to the stations, thus ensuring that only authorized stations will range to their satellites.

ILRS Products

All ranging data are available at the ILRS Data Centers for the Analysis Centers (ACs) to download for product development. More details on the ILRS products can be found in Section 7.

The ILRS ACs submit their ILRS product solutions to the ILRS data centers on defined schedules; the two ILRS Combination Centers retrieve and combine the AC solutions to generate the official ILRS products, which are then submitted to the DCs for archive and distribution.

Recent Developments

Data Quality Assessment and Review

The ILRS formed the Quality Control Board (QCB) that meets periodically via teleconference to examine data quality issues and to develop new procedures to highlight data quality problems. Tools and procedures have been implemented to better identify systems biases and provide rapid feedback to the stations. There has also been some strengthening in systems engineering to help identify bias sources.

Updates to Data Screening

The ILRS Operations Centers (OCs) at EDC and NASA are in direct contact with the ILRS stations; they collect and merge SLR data and transmit these data to the ILRS Data Centers (DCs) at EDC and CDDIS. In addition, the OCs perform quality control on all incoming data to ensure valid data are forwarded to the DCs for the user community. However, these tests were not extensive, and the checks performed at the two OCs were not identical. In the last few years, the OCs, with input from the NESC and the ILRS CB, developed a series of checks to harmonize their procedures; these checks identified the allowable values or range of values for every field in the CRD format. In August 2019, the OCs implemented an updated data screening process in order to coordinate data quality control (QC) and provide feedback on data issues to the stations. More importantly, both ILRS Operations Centers now utilize the same criteria for screening incoming data. Incoming data with fatal issues are screened out early in the process, and immediate warnings are sent to the stations. Data with minor issues (little of no impact on the data products) are passed on for processing and posting. Diagnostics are forwarded to the stations on a routine basis for necessary action. A summary of the new procedure is available on the ILRS website at: *https://ilrs.gsfc.nasa.gov/network/site_procedures/data_screening_procedure.html*.

ILRS Mirror Data Center

The GNSS Science Support Center (GSSC) at ESA's European Space Astronomy Center (ESAC) submitted an application to the ILRS in November 2018 to become an ILRS Data Center. The ILRS Governing Board accepted their application and designated ESAC/GSSC as an ILRS "Mirror Data Center". Although the role of the current ILRS Data Centers at CDDIS and EDC is much broader, where they are integrated into SLR operations and data flow, a Mirror Data Center at GSSC, once operational, will give the user community another access point for ILRS data, derived products, and service operational and status information. They may also provide other useful services to users.

Outreach Activities

The ILRS Central Bureau maintains the ILRS website on servers managed by CDDIS staff. The website is revised in a timely fashion to include recent news, meeting notices, mission updates, and other service developments.

In November 2019, the Journal of Geodesy published the "Special Issue: Satellite Laser Ranging", This issue, Volume 93, Issue 11, November 2019, editors Erricos Pavlis, Vincenza Luceri, Toshimichi Otsubo, Ulrich Schreiber, consists of twenty papers detailing recent developments in SLR. A list of papers published in the special issue is available at *https://link.springer.com/journal/190/93/11/page/1*.

Efforts are being made to bring IAG Services closer together; a joint meeting between the ILRS and the IGS was planned to take place at the 2020 IGS Workshop in August 2020, but has been delayed due to the global coronavirus pandemic.

Future ILRS Operational Activities

Updates to ILRS Data and Prediction File Formats

The ILRS Data Formats and Procedures Standing Committee (DFPSC) developed updates to both the prediction (CPF) and data (CRD) formats to accommodate advances in laser ranging since the original introduction of these formats in 2012. These modifications include changes required for time transfer activities, space debris tracking, and other potential applications. Further modifications allow for inclusion of additional information for enhanced diagnostics and correction of other issues that have been identified since the original implementation of the format. The ILRS infrastructure (stations, OCs, DCs, and ACs) are currently testing the new formats.

Updated Global Report Card Software

The ILRS Central Bureau has been generating global report cards on a quarterly basis since 1997 and a monthly basis since 2012. Some assumptions made, which were integrated into the initial software package that created reports prior to 2020, are no longer valid due to operational and technical improvements in the network, such as an increase in the number of targets, different ways in which stations track, and pass interleaving. A new version of the report card software is under development with the help of CDDIS staff. This new software incorporates changes to provide more accurate pass and normal point counts, satellite RMS, and LAGEOS bias information. In addition, the table summarizing LLR data will provide individual lunar retroreflector information. After review by the ILRS Central Bureau, the new software will be used operationally for all report cards generated after January 2020. The ILRS website will provide documentation about the new reports and differences with the previous versions. Furthermore, the new software will be used to generate the data for the previous years' reports (from May 2013 to December 2019), allowing users to compare data from pass years.

Section 5:

Emerging Technologies

Section 5: Emerging Technology

Authors: *Ivan Prochazka/Czech Technical University in Prague, Georg Kirchner/Austrian Academy of Sciences, Tom Varghese/Cybioms Corporation*

Introduction

New and improved technologies for satellite laser ranging and related applications are appearing. The key motivations are higher precision and accuracy, lower costs, higher productivity and new applications. This section of the report is mostly, but not exclusively, based on the technical papers presented at the International Workshops on Laser Ranging and ILRS Technical Workshops held in Potsdam (October 2016), Riga (October 2017), and Canberra (November 2018).

Detectors

The French (Courde et al., 2016) and German (Eckl et al., 2018) groups developed experimental detector packages based on new commercially available InGaAs/InP detection chips. These chips provide photon detection probability reaching 30% at 1064nm and timing resolution of about 20 ps rms. Such efficiency and timing resolution are comparable to the ones of Si based detectors at 532 nm. The use of such a detector in connection to NdYAG fundamental wavelength of 1064 nm in LLR is providing more than factor of 5x in energy balance in favor of InGaAs/InP.

The Chinese (Honglin Fu et al., 2016) group presented the first successful application of superconducting nanowire photon counting detector in LLR and space debris laser tracking. The superconducting detectors provide very high photon detection probability from visible to infrared wavelength, almost negligible dark count rate and high timing resolution. The challenge is a limited active area diameter, fiber optics signal coupling along with necessary cryo – cooling of the detector.

The Czech group (Prochazka et al., 2017) reported on a number of improvements of existing single photon detector packages optimized for SLR. The new version using the 200um diameter Si chip enables laser ranging with a single shot jitter as low as 10 ps RMS on a single photon signal level. Its effective dark count rate is typically 10 kHz for kHz gate rates. The key improvement of the detector version is also its long-term detection delay stability and its extremely low thermal dependence. The detection delay dependence is lower than 30 fs/K over the entire temperature range of -55… +55°C. The ultimate precision and long-term stability characterized by Time Deviation (TDEV) is better than 80 fs for integration times of hours.

For laser time transfer applications, the new generation of SPAD detector packages were developed for both ground and space segments. These devices were optimized for maximum timing stability within a broad temperature range. A new fully passive compensation of detection delay temperature dependence was developed. It provides detection delay dependence as low as 20 fs/K. Space qualified detector packages versions are available.

For optical tracking of orbiting space debris, the Czech group (Prochazka et al., 2018) developed a new version of high quantum efficiency photon counting package, which is capable of operation in both gated and cw mode. The gated mode presented before is dedicated for active laser ranging of orbiting space debris. The cw mode enables counting of photons scattered by orbiting space debris as a function of time. The cw mode dynamical range exceeds 3.5 orders of intensity. The light intensity curves enable determination of debris orientation, spin and several other parameters.

Timing Systems

In general, most of the SLR systems did or are converting to event timing concept. This change is enabling higher (kHz) operation rates, better temperature stability and better timing linearity.

The Latvian group continues upgrades of its timing systems A033 (Burak I, 2016), (Bespalko V, 2018). The main improvements are the increased maximum reading rate (30k to 1M readings per second depending on device version), single shot precision of several ps rms, temperature stability and non-linearity both on fraction of ps level. Epoch timing systems from this group are used at SLR systems worldwide (> 80 installations).

The Prague group continued in optimization of its New Pico Event Timer (NPET), which provides sub-ps timing jitter and femtosecond long term stability. The space qualified version is under development (Westin J, 2018) for applications in laser time transfer and similar space applications.

New SLR Station Concepts

A new concept of mounting whole laser units directly on the telescope has been tested successfully in Graz; both pico-second lasers and a more powerful space debris laser have been mounted on the telescope, and demonstrated the advantages of such a configuration. Considering the ongoing laser developments, it is expected that in the near future this concept will replace Coudé path systems.

The Stuttgart group demonstrated SLR with significantly higher repetition rates, up to 100 kHz; although such concepts still require some upgrades/changes in actual procedures, they offer significant advantages in terms of high data rates, high output/fast tracking of large numbers of targets. In addition, this offers advantages for automatic tracking and ranging.

Future Plans

Space Debris Laser Ranging

Most new SLR stations – planned or just being set up now – include a space debris laser ranging capability; several existing stations are also upgrading for that capability. Together with increasing numbers of stations with bi-static extension, this creates a network which can overcome the usual weather problems.

Tests for full daylight and blind nighttime debris laser ranging are ongoing.

Laser Time Transfer

Several space agencies are preparing or planning the laser time transfer ground to space. These measurements are prepared in connection with several space missions dedicated to high quality oscillators operating in space. The European Space Agency is preparing the ACES mission with the European Laser Timing module on board (Schreiber K.U. et al., 2018). The mission is under preparation for launch in 2021. The European SLR network is being prepared for participation in laser time transfer missions. The one-way delays of four European SLR systems were calibrated. Their station time scales are expected to be connected via fiber optical fiber network to several optical clock laboratories in Europe. The ACES follow-on mission called I-SOC with improved timing parameters is under preparation now. The performance of the hardware developed for the I-SOC laser time transfer is illustrated in Figure 5-1, where the overall system delay is plotted. The test setup consists of a rather long pulse laser source (Hamamatsu 42 ps FWHM), Start detector, SPAD detector with passive temperature compensation of detection delay and a two channel NPET timing device. The warmup part may be seen. The entire experiment was completed under standard laboratory conditions, no temperature control, etc. The long-term stability of the entire laser time transfer chain of the order of hundreds of femtoseconds over hours of operation may be seen. The stability expressed as Time Deviation (TDEV) is typically 80 fs for integration times of hours. These values illustrate the excellent performance and the long term stability of all the components of the laser time transfer chain including ground (SLR) and space segment.

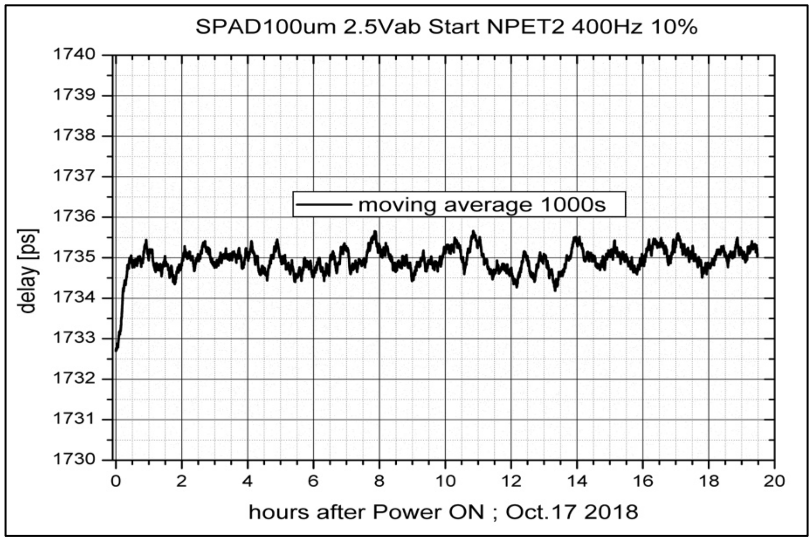


Figure 5-1. Long term stability of laser time transfer chain, I-SOC version 2018, ground tests results.

LIDAR

The high repetition rates, together with single-photon detection, allow simple implementation of LIDAR options as an add-on feature, with minimal effort; this can be useful for aircraft and/or cloud detection, a bonus for automatic SLR procedures.

Autonomous SLR

Autonomous tracking and ranging are already demonstrated in some stations (Mt. Stromlo, Zimmerwald etc.); all planned new SLR stations are implementing such operational procedures. One main concern there is security (internal, but also with respect to external access).

Compact, Eye-Safe, and Intelligent Multidisciplinary Optical Systems

Decades of SLR focused on technologies supporting millimeter accuracy and precision. Most of the process still relies on human operations, which has dependencies that often inhibit optimal operations and maximizing data yield. With the proliferation of satellites in all orbits and a need for dense coverage of the satellites, Cybioms Corporation, Electro Optic Systems, and others are developing systems, which are compact, eye safe, and demonstrating high levels of intelligence in operations for daytime and nighttime operations. This is particularly important when multidisciplinary work happens with such systems, especially in an observatory type environment. With a fusion of sensors, measuring a variety of instrumental and environmental parameters inside and outside of an observatory, the capability could exceed the level of human supervised or human managed operations.

Varghese (2017) reported the use AI for automatic sky detection of cloud coverage during day or night towards optimal tracking. Additional use of recognition technologies will serve to protect equipment in cases of quickly changing weather dynamics such as rain, lightning, etc. Furthermore, all machine activities can be systematically captured that will also allow forensics on any adverse event (if and when it happens). This will be used to augment training of employed AI technology that makes decisions about the health and safety of the system, to ensure smooth operation. One key concern for such automated operations is airspace safety, which needs to be managed with the appropriate selection of wavelengths or a companion safeguard system with ultrahigh reliability and redundancy. As always with any software driven systems, the extent of instrument/system level testing and operations to flush out any behavioral inconsistencies is a major part of the issue.

Cybioms Corporation and Electro Optic Systems are currently exploring a variety of ways to make the hardware of the optical systems compact, highly reliable, eye safe for MHz operations. In this regard, fiber lasers with a push towards 1.5-micron regime coupled with cryo-cooled nanowire technologies for detection is being studied. Beyond SLR, the new optical observatories that we are in the process of establishing will have faint optical imaging (magnitude 23 stars) with Cryo-cooled cameras with an intent to enable debris imaging including GEO.

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Section 6:

Mission Support

Section 6: Mission Support

Authors: *Carey Noll, Michael Pearlman*
Responsible Agency: ILRS Central Bureau

Overview

By the end of 2019, the ILRS routinely tracked nearly 120 satellites, over three times the number the service supported at its start in 1998 (Figure 6-1).

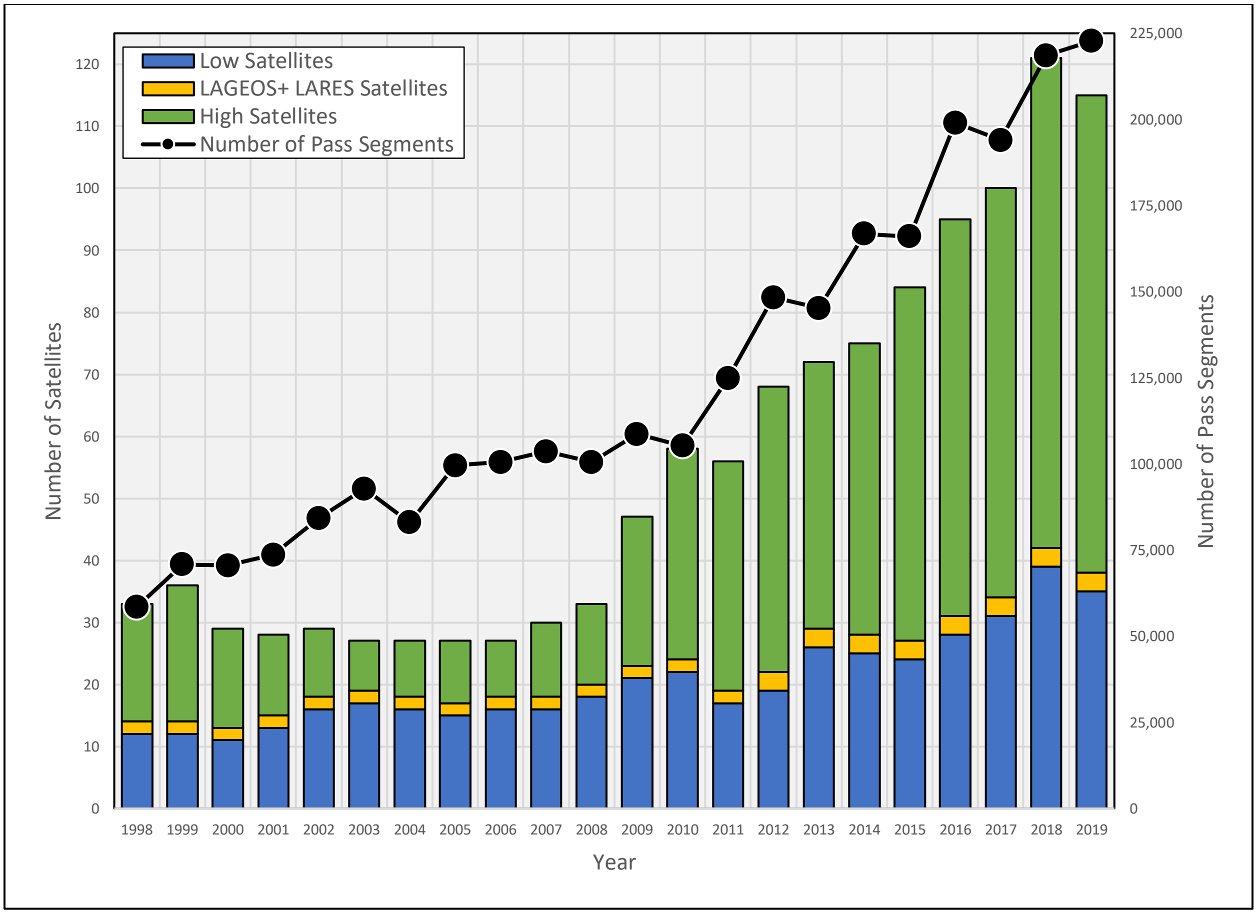

Figure 6-1. The number of missions supported through the years has continued to increase, mainly due to the increase in the number of GNSS satellites equipped with retroreflector arrays.

Stations in the ILRS network range to artificial satellites and the Moon; these satellites fall into four major categories:

- Geodetic
- Altimetric
- Space navigation and positioning (i.e., GNSS)
- Special/engineering

Examples of satellites in these categories are shown in Figure 6-2.

Geodetic satellites are dedicated, long-lived, passive retroreflector satellites, used in defining and improving the International Terrestrial Reference Frame (ITRF). These satellites include LAGEOS, LAGEOS-2, Etalon-1 and -2, and LARES. This application requires frequent and long-term tracking.

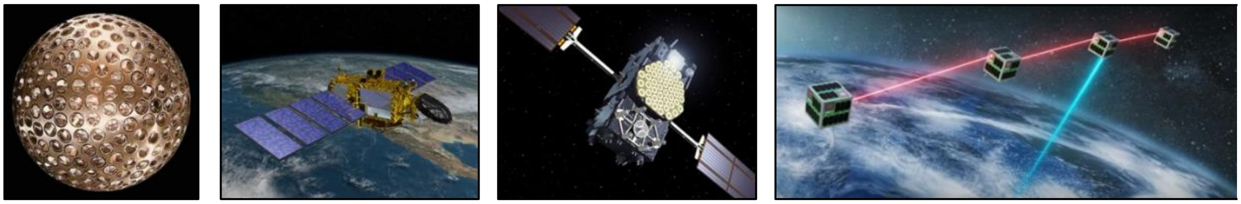

Figure 6-2. Some satellite missions currently supported by the ILRS; left to right: LAGEOS-1 (credit: NASA), Jason-3 (credit: NASA), a Galileo satellite (credit: ESA), SNET constellation (credit: TU Berlin).

Altimeter satellites, with typical life-times of 7 – 12 years, take measurements that allow us to better understand: the dynamics of sea surface topography, sea level, wave height determination, global ocean circulation, ice sheet thickness and topography, and land surface topography including biomass estimation. SLR is one of the techniques that provides Precision Orbit Determination (POD) and a means to calibrate and validate the altimeter instruments.

Space navigation and positioning satellites using microwave measurements give us precise geodetic positioning on the Earth for a wide range of applications and precise navigation in space. Laser tracking provides an independent means of calibrating the performance of these systems, further defining satellite force models, and directly tying their orbits into the SLR reference frame with its well-defined geocenter and vertical scale height.

Special or engineering satellites usually have unique, short-term scientific or engineering goals, such as testing the performance of new retroreflector designs, studying in-orbit satellite dynamics, or intercontinental time transfer experiments.

This section of the 2016-2019 ILRS report provides a summary of current, past, and future missions tracked by stations in the ILRS network as well as dedicated campaigns supported during the 2016-2019 timeframe.

Current Missions

In the 2016 to 2019 time period, the ILRS supported 139 distinct artificial satellite satellites and lunar reflectors in the categories listed above. A summary of the network tracking during this three-year period is shown in Figure 6-3; tracking totals by station can be found in figures in Section 8 (ILRS Network). As can be seen from the charts, the ILRS has a wide range of performance among the stations.

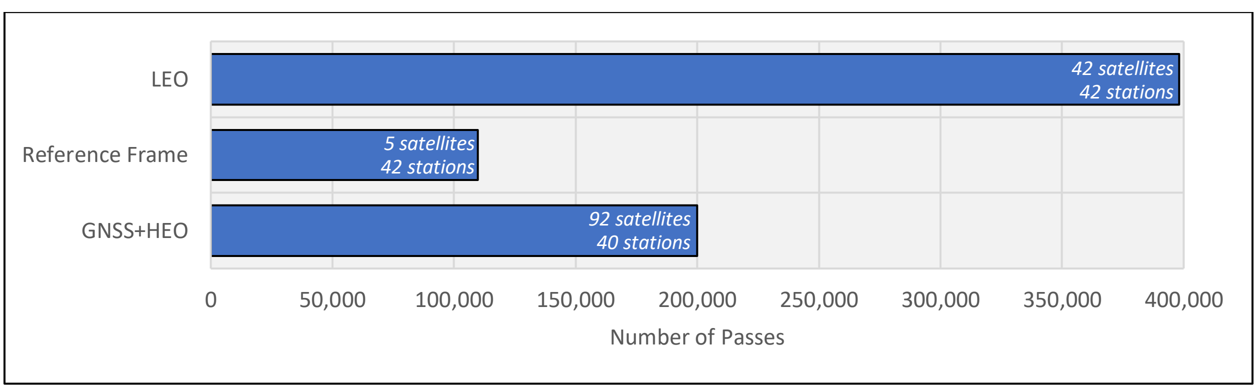

Figure 6-3. Satellite support by stations in the ILRS network in 2016-2019.

Lunar Targets

Stations in the ILRS network with lunar capability also tracked the five reflector arrays on the Moon. The measurement distribution w.r.t. of the reflectors is still dominated by the Apollo 15 reflector, but its impact was reduced to 69% (see Figure 6-4). When looking at the statistics between 2016 and 2018 (Figure 6-4) the distribution between the smaller reflectors was evened out and the Apollo 15 reflector has a share of only 39%. It should be noted, for the Apache Point APOLLO station, only the total number of normal points is approximately known; no normal points after 2016 were distributed up to now and could not be included in Figures 6-4 and 6-5.

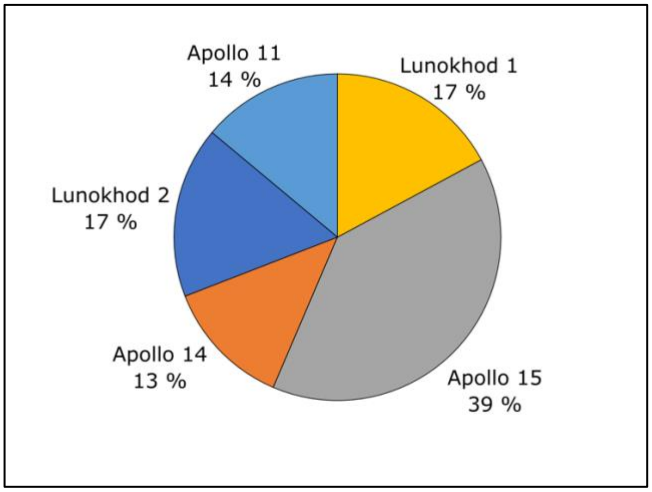

Figure 6-4. Lunar target statistics (1970-2018) by reflector array.

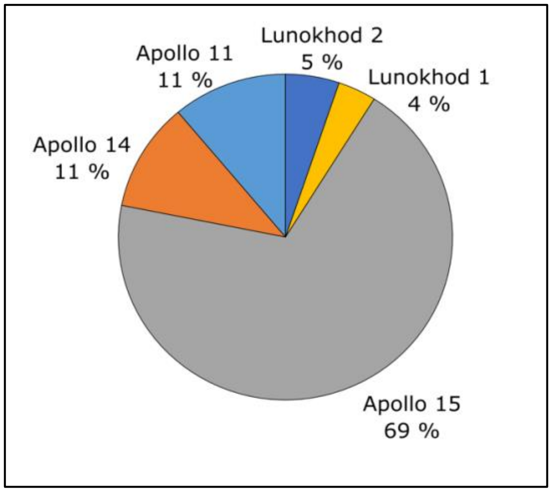

Figure 6-5. Lunar target statistics (2016-2018) by reflector array.

Processing Requests for Mission Support

The ILRS supports scientific and engineering research applications and programs; the service's primary emphasis, however, is the support of the IAG's Global Geodetic Observing System (GGOS) and the geodetic satellites that form the basis for the maintenance and improvement of the International Terrestrial Frame (ITRF). At the end of 2019, the ILRS network ranged to more than 120 satellites; missions continue to submit additional requests for tracking support. The ILRS reviews new Mission Support Requests (MSRs) on the basis of laser tracking need and the likelihood of mission success. Although the ILRS tries to accommodate all new tracking requests, the submission of a request does not guarantee ILRS support.

New requests for ILRS tracking support must be submitted to the ILRS Central Bureau, reviewed by the Missions Standing Committee (MSC), and following MSC recommendation, approved by the Governing Board.

Mission contacts must submit new requests, using the Mission Support Request Form available on the ILRS website, to the ILRS Central Bureau at least six months prior to launch or when the mission expects tracking support to begin. The MSR must include contact information, objective of the mission and its need for laser tracking support, satellite and retroreflector information, and a mission concurrence signature page. Following a positive review by the MSC, the CB submits the MSR to the Governing Board for final approval.

Once tracking support is approved, the ILRS Central Bureau works with the new missions to establish the level of tracking, the schedule, the points of contact, and the channels of communication.

Some satellites requesting ILRS support must (or can) only be tracked by laser ranging under certain constraints or conditions. These “restricted tracking” missions include satellites equipped with: 1) sensors that could be damaged if illuminated by a laser beam, 2) corner cubes that may not be visible under certain geometric conditions, or 3) detectors that only can handle a certain level of power produced by an SLR station. In order to support these missions, the ILRS, through the CB and MSC, must develop mission-specific procedures for restricting SLR tracking; this process often takes considerable time, coordination, and interaction between the CB, the MSC, the mission, and the stations. The ILRS CB and MSC must ensure that the mission requirements are met in a safe manner and that all participating stations range to the satellite following established guidelines. The ILRS CB works with these missions by providing station configuration information for their review. The CB also interacts with the stations, coordinating how and under what conditions they can range to the satellite. Examples of recent restricted tracking missions include the Sentinel-3 satellites and ICESat-2.

Recent Developments in Mission Support

The ILRS acknowledges the 40th anniversary of the launch of LAGEOS (May 04, 1976) and the 30th anniversary of the launch of Ajisai (August 13, 1986) during this reporting period; both satellites continue to satisfy investigator requirements in solid Earth dynamics and reference frame evolution. In addition, NASA celebrated the 50th anniversary of the first Moon landing on July 20, 1969 where astronauts installed retroreflector arrays and thus the birth of Lunar Laser Ranging.

New Mission Support Request Form

The ILRS Missions Standing Committee (MSC), in conjunction with the CB, developed an update to the ILRS Mission Support Request form. The new form includes additional fields needed by the ILRS to assess the mission requirements for future ILRS tracking support. The form is easier to fill out and read; some additional questions were added while obsolete, previously requested information has been removed. The new mission support Request Form, along with mission support guidelines, are available on the ILRS website at: *https://ilrs.cddis.eosdis.nasa.gov/missions/mission_support/new_mission_support.html.*

Guidelines for New Mission Support

The ILRS CB has been working with the MSC to clarify and strengthen the guidelines for missions requesting tracking support. In addition to the review of a complete Mission Support Request Form, some of the questions being considered are:

- Does SLR provide a unique capability that other tracking systems cannot? Is SLR the primary or secondary tracking technique? Can the tracking requirement be met by another technique?
- What added value will SLR data provide to the data products?
- Has the mission sufficiently quantified its tracking requirement (accuracy, data volume, coverage, etc.)?
- Does the mission have a vulnerable payload aboard that will require special tracking procedures?
- What is the procurement source of the retroreflector array(s)? Does the design include accommodation for the velocity aberration?
- Has the signal link budget been estimated either through comparison with spacecraft already tracked by SLR or through the link equation?

- Have provisions been made to provide reliable predictions in the required format? Has this source tested their predictions or are there plans to do such testing?

The ILRS MSC and CB addressed these questions and developed clear guidelines that would need to be considered when reviewing future mission support requests. The guidelines are now posted on the ILRS website: *https://ilrs.gsfc.nasa.gov/missions/mission_support/new_mission_support.html*.

Revised GNSS Tracking Strategy

The ILRS has been working with the IGS and other interested parties to develop and finalize a GNSS tracking strategy that would satisfy both mission and user requirements. For some applications, users want denser tracking on a few satellites. For other applications, users want some tracking on the full complex of GNSS satellites, even if that tracking is sparse. In addition, there are also requests for focused campaigns, in particular, for tracking GNSS satellites while going through Earth shadow to study the effects of radiation pressure. We presently have over 60 GNSS satellites (GLONASS, Galileo, BeiDou) on the ILRS roster. More will be added in the near future. The total could reach nearly 100 when GPS is added in the 2024 timeframe.

The ILRS implemented the new strategy for laser ranging to GNSS targets in 2019. These tracking guidelines for the stations were published on the ILRS website at: *https://ilrs.gsfc.nasa.gov/missions/GNSS_Tracking_Strategy_2019.html*. The main points that the ILRS has agreed to implement are as follows:

- GNSS tracking will continue to be prioritized with the other ILRS satellites by the standard ILRS priority scheme (by altitude and inclination);
- Four GNSS satellites will be identified by each constellation (Galileo, GLONASS, and BeiDou) for intensive tracking, with three sectors (at least 2 normal points each) spaced widely apart over the pass. If stations cannot obtain three sectors they should try to get two sectors. These four satellites per constellation would be selected by the constellation and would have the highest priority among the GNSS satellites.
- All of the remaining GNSS satellites would be tracked by the stations on an as time available basis; selection of targets should be determined by the stations for data yield, but stations are asked to try to diversify among all three constellations because we need some data on all three.
- Special tracking campaigns will be scheduled as time permits, to support special studies.
- Stations will be urged to set their tracking schedules to support all of the GNSS constellations.

Contacts for the GLONASS, Galileo, and BeiDou missions selected four primary, high priority satellites that were incorporated into the ILRS priority list.

New Missions (2016-2019)

During the 2016-2019 time period, the missions listed in Table 6-1 where accepted by the ILRS and tracking support began shortly after launch. A total of 11 missions totaling 15 satellite targets were reviewed by the Missions Standing Committee, approved by the ILRS Governing Board, and added to the ILRS priority list. Due to instrument vulnerabilities, SLR ranging to the Sentinel-3A and -3B and ICESat-2 satellites is restricted to a subset of stations approved by the mission and the CB. These stations obtain satellite predictions directly from the mission facilities.

Table 6-1. New satellite missions supported by the ILRS starting in 2016-2019.

Mission	Launch Date	Sponsor	Application	ILRS Support
Jason-3	17-Jan-2016	NASA, CNES, Eumetsat, NOAA	Oceanography	POD
Sentinel-3A Sentinel-3B	16-Feb-2016 25-Apr-2018	ESA, Eumetsat	Marine observation	POD
Geo-IK-2	04-Jun-2016	JSC ISS Russia	Earth remote sensing	POD
Tiangong-2	15-Sep-2016	CMSE China	Manned spaceflight	POD
TechnoSat	14-Jul-2017	TU Berlin Germany	Engineering	Engineering
SNET (4 satellites)	01-Feb-2018	TU Berlin, Germany	Engineering	Engineering
PAZ	22-Feb-2018	HISDESAT	Weather prediction	POD
GRACE-FO (2 satellites)	22-May-2018	NASA, GFZ	Gravity field	POD
ICESat-2	15-Sep-2018	NASA	Ice sheet monitoring	POD
LightSail-2	02-Aug-2019	The Planetary Society	Engineering	POD

Past Missions (2016-2019)

During 2016-2019 time period, the ILRS support for the missions, listed in Table 6-2, was no longer required.

Table 6-2. Missions completed for ILRS tracking support in 2016-2019.

Mission	Start/End Date	Sponsor	Application	ILRS Support
BLITS-M*	27-Dec-2019	Roscosmos, JC "RPC "PSI"	Calibration of SLR stations	POD
GRACE	Mar-2002 – Apr-2018	NASA/GFZ	Gravity field	POD
Jason-2	Jun-2008 – Oct-2019	NASA, ESA, EUMETSAT, NOAA	Remote sensing	POD
LightSail-2	Aug – Sep 2019	The Planetary Society	Engineering	POD
Lomonosov	Sep – Dec-2019	Moscow State University	Atmosphere research	POD
PN-1A	Nov-2015 – Feb-2018	BAAC	Engineering	POD
SpinSat	Dec-2014 – Mar-2017	NRL	Atmospheric density	POD
STSAT-2C	Mar-2013 – Aug-2019	MEST, KAIST	Spacecraft development	POD
Tiangong-2	Aug-2018 – Jan-2019	CMSE China	Manned spaceflight	POD

*Note: BLITS-M experienced a launch failure and never achieved its target orbit.

Special Tracking Campaigns (2016-2019)

The ILRS CB organizes special dedicated campaigns to provide more intensive or increased tracking on select missions. During 2016-2019, the ILRS conducted three major campaigns as discussed below. Several other mission-specific campaigns for concentrated tracking on single satellites were also conducted during this time period, e.g., QZS satellites, IRNSS-1B, etc.

GREAT: Galileo gravitational Redshift test with Eccentric sATellites

At the 2015 ILRS Technical Workshop in Matera Italy, colleagues with the Center of Applied Space Technology and Microgravity (ZARM) at Bremen University, Germany and the Systèmes de Référence Temps-Espace (SYRTE) laboratory, France agreed on an experiment to test the gravitational redshift by conducting an SLR tracking campaign on Galileo-201 and -202. Due to technical difficulties at launch, the satellites did not reach their intended orbits, but they were eventually maneuvered into eccentric/elliptical orbits, which induced periodic modulations of the gravitational redshifts. The on-board atomic clocks allowed for a long-term assessment in the variation of the redshift and for a determination of the accumulated relativistic effects. In conjunction with the IGS Multi-GNSS Experiment (MGEX) orbit products, SLR data were used to characterize the radial orbit errors. The ILRS supported the GREAT experiment from May 01, 2016 through April 07, 2017. During the campaign, ILRS stations were asked to concentrate tracking on Galileo-201 and -202 during the first seven days of every month for one year, tracking Galileo-201 more intensively. Stations were asked to take one or two normal points (5 minutes in duration) every fifty minutes over the pass. More information on the experiment is available on the ILRS website: *https://ilrs.gsfc.nasa.gov/missions/GREAT_exp.html*.

Results *(Javier Ventura-Traveset, ESA/ESAC)*

Europe's Galileo satellites 5 and 6 (Galileo-201 and -202), provided a historic service to the physics community worldwide by enabling the most accurate measurement ever of the gravitational redshift and thus of local position invariance, an integral part of the Einstein equivalence principle. For this ESA launched a dedicated research activity with two independent research groups, led respectively by the SYRTE Observatoire de PARIS-PSL (*https://syrte.obspm.fr/*) in France and Germany's ZARM Center of Applied Space Technology and Microgravity (*https://zarm.uni-bremen.de/en/*), coordinated by ESA's Galileo Navigation Science Office.

In support to these tests, a specific ILRS campaign took place during the years 2016-2017, which allowed us to very precisely the radial one-way residuals with respect to the modelled orbit solution of the two Galileo satellites, allowing, in turn, to quantify the systematics due to the orbital modelling in order to obtain a robust error budget.

As a result of these tests, an improvement of the gravitational redshift by a factor of 5 was achieved, providing, to our knowledge the first reported improvement since more than 40 years of the NASA Gravity probe A (1976) equivalent test. The support from the ILRS proved essential for this achievement.

Scientific References:

S. Hermann et al. "Test of the gravitational redshift with Galileo satellites in an eccentric orbit," *Physical Review Letters, Vol. 121, Iss. 23, p. 231102, 7 December 2018.*

P. Delva et al. "A gravitational redshift test using eccentric Galileo satellites" *Physical Review Letters, Vol. 121, Iss. 23, p. 231101, 7 December 2018*

LARGE: LAser Ranging to GNSS s/c Experiment

The ILRS established the LAser Ranging to GNSS s/c Experiment (LARGE) Study Group in 2013 to help expand the GNSS tracking coverage by the ILRS network. The GNSS satellite constellations with retroreflector arrays of main interest are those constellations with global coverage, including GLONASS, BeiDou, Galileo, and future GPS.

SLR tracking of GNSS satellites has been a network challenge, which will only become more demanding as additional satellites are launched in each constellation, and as the GPS-III retroreflector satellites join the roster in the middle of the next decade. Over the last few years, the ILRS has received differing requests from both the GNSS providers and users for SLR tracking support; some requesting intensive tracking on a few GNSS satellites and others requesting sparse tracking on as many GNSS satellites as possible. Intensive tracking was characterized by three tracking segments of at least two normal points each, with the segments taken during the ascending, middle, and descending regions of the pass. Sparse tracking was at the level of one segment per pass.

In 2018, the ILRS conducted two LARGE tracking campaigns, to examine how the service might combine the two options and address the needs of both communities. In the first campaign (February 15 through May 15, 2018), each GNSS constellation identified four primary and four secondary satellites for intensive tracking. In the second campaign (August 01 through October 31, 2018) the Galileo and Compass/BeiDou constellations selected eight satellites each for high priority tracking; GLONASS chose to identify only four. Since only four satellites were designated for GLONASS, the stations were instructed to try to obtain as many passes on these satellites as possible. Predictions for all the other satellites in each constellation were issued, and thus stations could continue to track these satellites on a non-interference basis with the LEO, LAGEOS, and selected GNSS satellites at higher priority. The designated LARGE GNSS satellites were interleaved on the priority list to try to give each constellation an equal chance of tracking.

The campaigns demonstrated that the network could expand SLR tracking coverage, even operating under the mixed mode strategy, but there was an imbalance in the tracking coverage for the three constellations and that further, more detailed instructions to the stations for effective tracking of GNSS satellites would be necessary. Additional observations about the campaign can be found in the monthly reports from both 2018 LARGE campaigns available on the ILRS website at:

https://ilrs.gsfc.nasa.gov/science/ILRS_LARGE_sg/LARGE_activities/LARGE_activities.html

These tests were the basis for the initial tests of new tracking strategies tried by the ILRS. Other strategies are under discussion with the IGS.

Etalon Campaign

The Etalon data contribution to the reference frame is still very sparse and yet holds potential for improvement in the determination of Earth Orientation Parameters (EOPs). The Analysis Standing Committee (ASC) requested that the ILRS organize a tracking campaign in 2019 to increase data volume on Etalon-1 and -2. During the three-month campaign, held February 15 through May 15, stations were asked to obtain at least one pass per day on each of the two satellites, with NPs on the ascending, middle and descending portions of the pass, with three normal points per segment.

The stations have been able to strengthen their ability to track GNSS altitudes, leading us to believe that a reasonable improvement in Etalon data can be achieved with some increase in effort. The ILRS ACs analyzed the results from the actual data analysis of the Etalon campaign period, focusing on the EOP improvement. Data from the same timeframe in 2018 were reanalyzed in order to have results compared to exactly the same IERS C04 series. The results showed that the additional Etalon data makes a significant difference, bringing the ILRS EOP product a lot closer to the "final" IERS series (which is ~90% a GNSS product). The campaign summary report is available on the ILRS website (*https://ilrs.gsfc.nasa.gov/docs/2019/Etalon_1and2_2019_Campaign.pdf*). The ILRS Analysis Coordinators have requested that the network do their best to increase their collection of Etalon data on a permanent basis.

Future Plans

New Missions

New mission support requests were received and approved by the ILRS for several missions in the near future, as summarized in Table 6-3 below.

Table 6-3. New satellite missions approved for ILRS tracking support in 2019 and beyond.

Mission	Planned Launch	Sponsor	Application	ILRS Support
Astrocast*	01-Apr-2019	ETH Zurich and Astrocast SA	Positioning	POD
COSMIC-2	25-Jun-2019	UCAR	Atmospheric research	GNSS orbit validation
ELSA-d	Nov-2020	Astroscale	Engineering research	POD
LARES-2	Fall 2020	ASI	Positioning, geodesy	POD
NISAR	2021	NASA/JPL, ISRO	Earth observation	POD

*Note: Select stations tracked the two Astrocast Precursor satellites in 2019 as per request of mission; general tracking by entire ILRS network has not yet been activated.

By the middle of the next decade, the ILRS anticipates the emergence of the new GNSS constellations (e.g., GPS-III) to be included in the ILRS tracking roster.

In the next few years, a new generation of more accurate and efficient lunar reflectors are expected to be deployed on the lunar surface. LLR again has shown a strong capability to test Einstein's relativity theory and to improve the limits for a number of relativistic parameters. In addition, lunar science and many quantities of the Earth-Moon dynamics are being widely be studied. As a next step, the ILRS is planning a new structure (e.g., a working group or standing committee) to support LLR within the ILRS and to link all LLR contributors, from observatories to science.

GNSS Eclipse Campaign

Solar radiation pressure is a significant surface force on GNSS satellites. Special campaigns have been requested by ESA to track GNSS satellites as they approach solar eclipse conditions to see the effect on the satellite orbits. Intensive tracking will be scheduled over the course of several days at a time and might involve a couple of satellites at a time. The first campaign will be scheduled for 2019.

Section 7:

ILRS Analysis Activities

Section 7: ILRS Analysis Activities

Authors: *ILRS Analysis, Combination, Associate, and Lunar Associate Analysis Center Representatives*
Editors: *Erricos Pavlis, Carey Noll*

Introduction

SLR and LLR Analysis Centers (ACs) and Associate Analysis Centers (AACs) utilize the laser ranging data to generate ILRS derived products on an operational basis, typically daily or weekly depending on the product, using accepted standards. These official ILRS products include positions and velocities of ILRS network stations, Earth Orientation Parameters (EOPs), and precise orbits for selected satellites (LAGEOS and Etalon). AACs generate specialized products, such as station data quality reports. Two Combination Centers (CCs) generate operational ITRF products based upon the individual AC solutions; these products include daily/weekly station positions and daily resolution Earth orientation products and weekly combination of satellite orbit files for LAGEOS-1/-2 and Etalon-1/-2. Lunar Associate Analysis Centers (LAACs) process data from lunar-capable stations in the ILRS network to generate a variety of scientific products.

A list of currently approved ILRS ACs, CCs, AACs, and LAACs is maintained on the ILRS website at: *https://ilrs.gsfc.nasa.gov/science/analysisCenters/index.html* and listed in Tables 7-1, 7-4, 7-5, and 7-7.

ILRS Analysis Centers

Eight centers have been qualified as ILRS Analysis Centers (see Table 7-1). These centers are required to provide weekly submissions of Earth orientation parameters and station coordinates and precise orbit products (LAGEOS-1 and -2 and Etalon-1 and -2) that are included in the production of the official ILRS combination product. The Analysis Centers are appointed based on their demonstrated performance in both the rigor of their analyses and the punctuality with which their weekly solutions have been submitted to the ILRS Combination Centers.

Table 7-1. ILRS Analysis Centers (ACs)

Code	AC Title and Supporting Agency
ASI	Agenzia Spaziale Italiana, Centro di Geodesia Spaziale "G. Colombo" (ASI/CGS), Italy
BKG	Bundesamt für Kartographie und Geodäesie (BKG), Germany
DGFI	Deutsches Geodätisches Forschungsinstitut-Technische Universität München (DGFI-TUM), Germany
ESA	European Space Agency/ European Space Operations Centre (ESA/ESOC), Germany
GFZ	Helmholtz Centre Potsdam German Research Centre for Geosciences (GFZ), Germany
GRGS	Groupe de Recherche de Géodésie Spatiale (GRGS), Paris Observatory, France *(not active since mid-2016)*
JCET	Joint Center for Earth Systems Technology/Goddard Space Flight Center (JCET/GSFC), USA
NGSF	NERC Space Geodesy Facility (NSGF), United Kingdom

ASI/CGS (Agenzia Spaziale Italiana, Centro di Geodesia Spaziale "G. Colombo"), Italy

Author: *G. Bianco (ASI), V. Luceri (e-GEOS S.p.A.)*
Responsible Agency: Italian Space Agency/Space Geodesy Center “G. Colombo”

Areas of Interest

The ASI Space Geodesy Center "G. Colombo" (CGS) has contributed to ILRS since the beginning of the Service activities both as a fundamental station and analysis center (AC). The data analysis team is daily involved in the analysis of SLR, VLBI and GNSS data, collected by the worldwide networks, to estimate fundamental geodetic parameters. The SLR data analysis activities at the ASI/CGS started in the 80’s and, since then, have been focused primarily on global, extended solutions in support of the reference frame maintenance. Its main interest is in the areas of tectonic plate motion, crustal deformation, Earth rotation and polar motion, Earth gravitational field, Terrestrial Reference Frame, satellite orbit determination, climate change.

The analysis center participates in national and international programs on advanced SLR applications, like Quantum Communication and Space Debris Tracking.

The ILRS Governing Board recognized the center’s continuous and rigorous contribution and appointed the ASI/CGS as one of the official ILRS Analysis Centers when the ILRS AC structure was finalized (2004).

Information on the CGS and some of the analysis results are available at the CGS website GeoDAF (Geodetic Data Archiving Facility, *http://geodaf.mt.asi.it*).

Recent Progress and Analysis Center Improvements

In the year 2016-2019, the ASI/CGS has been deeply involved in the ILRS activities, mainly in support of the reference frame maintenance and under the coordination of the Analysis Standing Committee (ASC).

The ASI AC main contributions were:

- ILRS official products:
    - weekly submission of loosely coordinate/EOP solutions estimated using LAGEOS and Etalon data and following the project requirements. The product is the ASI/CGS input to the official ILRS combined SSC/EOP product. Figure 7-1 below shows a comparison between the ASI solution and the combined ILRS-A in terms of 3 dimensional WRMS of the core site residuals with respect to ITRF. It is clear the use of the new model ITRF2014 at the beginning of July 2017.

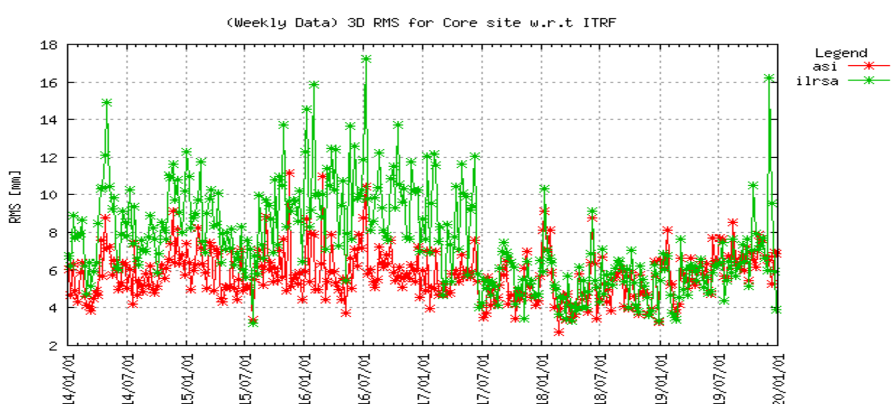

Figure 7-1. ASI and ILRSA 3D coordinate residual WRMS A.

  - daily submission of loosely coordinate/EOP solutions estimated using LAGEOS and Etalon data and following the ASC requirements. The product is the ASI/CGS input to the official ILRS combined EOP product.
  - weekly orbits: estimated state vectors of the 4 satellites, LAGEOS and Etalon, are distributed weekly, as requested by the ASC, in the ITRF reference frame as input to the official ILRS combined orbit product.
- "Station Bias determination and monitoring": the characterization of station systematic errors started in the 2000 and then was turned into a specific ASC Pilot Project with the aim to recover real errors from the data analysis. Figure 7-2 below is one of the first time series submitted in 2018 showing a clear range bias not included in the applied model. In the reported period several time series of weekly station range biases were submitted to the ILRS Combination Centers, according to the ASC guidelines. More details in the ASC report in this volume.

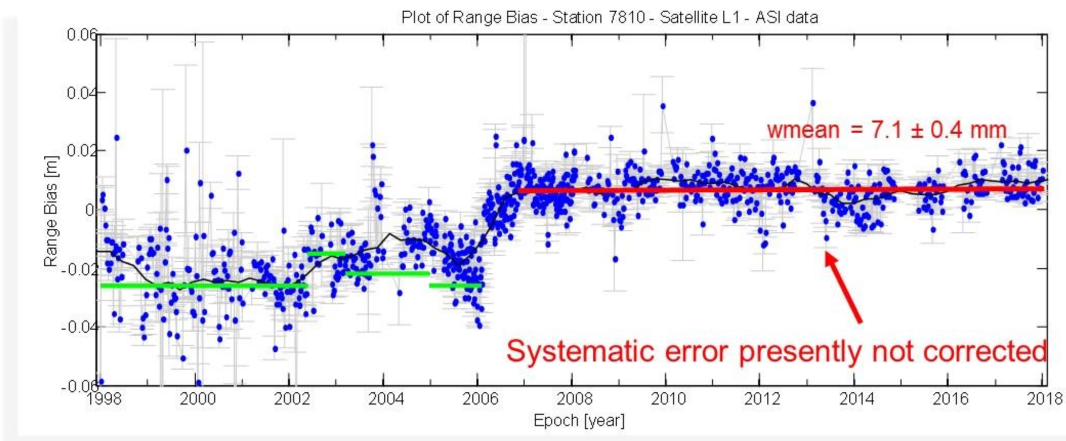

Figure 7-2. Zimmerwald range biases for LAGEOS.

- "Station qualification": ASI/CGS is one of the ACs designated by the ASC to validate the data from new or upgraded sites or after an earthquake.
- "CRD validation": ASI/CGS is one of the ACs designated by the ASC to validate the data submitted by the station in the new CRD format.
- Participation to all the ASC Pilot Projects.

The ASI/CGS analysis activities extend beyond the accomplishment of its role within ILRS and were addressed in the following main application fields.

- International Terrestrial Reference System (ITRS) maintenance:
  - production of IERS oriented products (global SSC/SSV and EOP time series) regularly performed as ASI/CGS operational EOP series: 1-day estimated EOP, from LAGEOS and Etalon data, are available at the IERS website *ftp://hpiers.obspm.fr/iers/series/operational/*;
  - generation of the multi-year solution, from LAGEOS-1 and -2 data (since 1983). Global network SSC/SSV and 3-day EOP (x, y, LOD) are the main parameters estimated in this solution and available under request.
- EOP excitation functions: production of the geodetic excitation functions from the ASI/CGS estimated EOP values for IERS (available on the ASI geodetic website *http://geodaf.mt.asi.it*): the daily geodetic excitation functions are produced every Tuesday along with the operational weekly SLR solution, staked and compared whenever possible with the atmospheric excitation functions from the IERS SBAAM, under the IB and non-IB assumption, including the "wind" term;

- Orbit determination of space targets (e.g., space debris) using positioning data acquired with the Space Debris Observatory at ASI/CGS.

Technical Challenges and Future Plans

Most of the current activities will continue, with particular attention to the ILRS and IERS oriented products.

The activities for the next ITRF2020 started in 2019 and will continue in the next 2 years in order to fulfill the ASC request for the generation of the ILRS contribution. Weekly loosely solutions, from 1993.0 to 2021.0, with estimated site coordinates and EOPs and obtained using LAGEOS, Etalon and LARES data will be prepared according to the ASC guidelines.

Deeper investigations will be directed to the low degree geopotential zonals and precise orbit determination.

CC/AC/AAC/LAAC Personnel

The Italian Space Agency is the owner of the Space Geodesy Center and is the decision-making body, Giuseppe Bianco, director of the ASI/CGS, is the ASI manager of the Analysis Center. The activities of the Analysis Center are performed by e-GEOS S.p.A. (formerly Telespazio) since the very beginning in the 80's. The team is composed by 6 people involved in SLR, VLBI and GNSS data analysis. The SLR data analysis activity is coordinated by Vincenza Luceri.

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Areas of Interest

Within the Analysis Standing Committee (ASC), the SLR Analysis Center (AC) at BKG derives Terrestrial Reference Frame (TRF) solutions from ILRS SLR data for the “pos+eop” routine daily and weekly services as well as for pilot projects scheduled. Within the routine operations, LAGEOS and Etalon SLR data are processed in 7-day arcs, and all parameters (station positions, Earth Rotation Parameters, orbits, range biases) are estimated on the observation level in one common step. Additionally, several QC steps (Helmert transformations, orbit comparisons) are performed. The analysis software used is the Bernese GNSS Software in its SLR development version (see Dach et al., 2015, Thaller et al., 2009, and Thaller et al., 2012). The upgrading of the analysis software to meet the ILRS ASC requirements is done in cooperation with AIUB.

During the reporting period the following reports were produced:

Koenig D, Grahsl A, Thaller D (2017) BKG’s Contribution to the ILRS Pilot Project on Systematic Errors, Proceedings of the 2017 ILRS Technical Workshop, Riga, 2017, URL: *https://cddis.nasa.gov/2017_Technical_Workshop/docs/papers/session2/ilrsTW2017_s2_paper_DKoenig.pdf*.

Koenig D, Meyer U, Thaller D, Dach R (2018) The BKG Reprocessing for the ILRS Pilot Project on Systematic Errors, Geophys. Res. Abstr., Vol. 20, EGU2018-13137, 2018, EGU General Assembly 2018.

Koenig D, Meyer U, Thaller D (2018) Further Studies on the Influence of Range Biases, Proceedings of the 21st International Workshop on Laser Ranging, Canberra, 2018, URL: *https://cddis.nasa.gov/lw21/docs/2018/papers/Session5_Koenig_paper.pdf*.

Recent Progress and Analysis Center Improvements

In November 2016, the person in charge of the SLR-AC at BKG switched from Maria Mareyen to Daniel Koenig with a vacancy of several months.

BKG has contributed TRF solutions to the SSEM pilot project (PP) according to the specifications requested by the ASC. The results obtained by the BKG solution were presented at the ILRS Workshops 2017 (Riga) and 2018 (Canberra) as well as at the EGU General Assembly 2018. Especially interesting during the current reporting period have been the difference of the TRF scale w.r.t. SLRF2014 as well as the behavior of the ground stations’ range biases (RB).

For illustration, in Figure 7-3 the Differential Scale (DS) between a LAGEOS-only solution and the a priori SLRF2014 is plotted. It can be seen that in case of RB for each station (SSEM-PP) there is higher scatter as opposed to the case of RB set up only for selected stations. On the other hand, forming annual mean values (not shown here) reveals that in the SSEM-PP case the DS time series stays roughly more stable at negative values whereas in the case of RB set up only for selected stations the mean values clearly rise from negative to positive values.

An investigation of RB time series stemming from different solutions suggests that the time series obtained for stations McDonald (7080) as well as Yarragadee (7090), see Figure 7-4, represent the two types of RB behavior of all other core stations. Eminently, the RB estimated for Yarragadee form time series of very low scatter and median of only a few mm. However, a small but significant offset of the

Etalon combined RB of solution LS_EC ('LS_EC (Etalon)') w.r.t. the LAGEOS combined RB ('LC') is detected. Though staying remarkably stable the RB time series for McDonald reveal a larger scatter as well as some outliers.

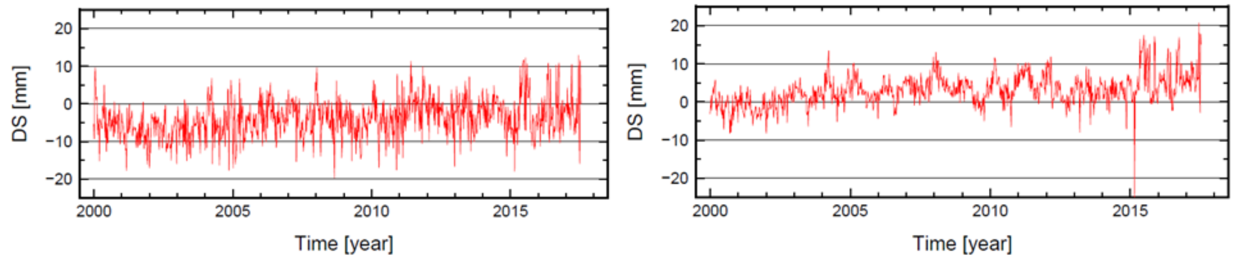

Figure 7-3. Differential scale between a LAGEOS-only solution and SLRF2014 (a priori) (left: SSEM-PP with separate range biases for LAGEOS-1 and -2 for each ground station, right: solution following specifications of operational processing, i.e., range bias for selected stations only).

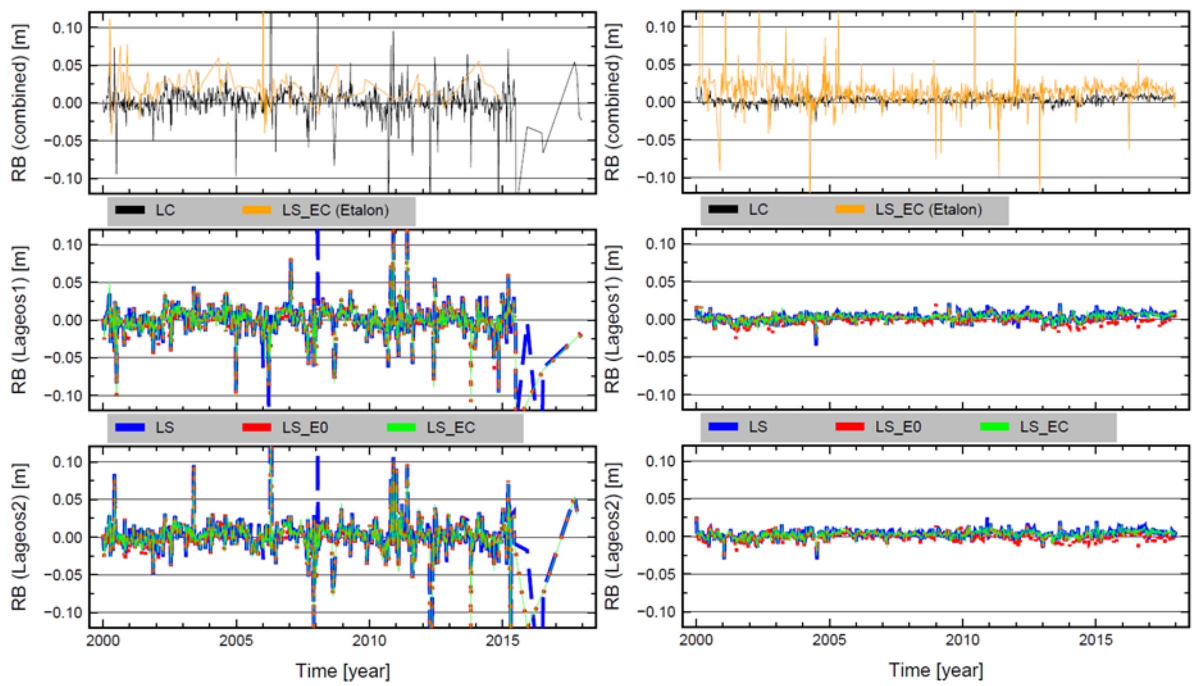

Figure 7-4. Range Biases (RB) estimated (left: McDonald 7080, right: Yarragadee 7090; 'LC': LAGEOS-only/combined RB, 'LS': LAGEOS-only/separate RB, 'LS_E0': LAGEOS+Etalon/separate RB for LAGEOS/no RB for Etalon, 'LS_EC': LAGEOS+Etalon/separate RB for LAGEOS/combined RB for Etalon)

In order to meet the ASC requirements for deriving the TRF solutions required (operational and PP) the SLR analysis software used has steadily been upgraded by implementing the IERS2010 mean-pole, the proper handling of SLR wavelength information, and the processing of the new satellite Center-of-Mass (CoM) tables provided by NSGF. Moreover, the transition to ITRF2014 with PSD corrections as a priori TRF was implemented.

Technical Challenges and Future Plans

Over the next two years it is intended to augment the capabilities of the AC by developing tools for visualizing TRF results as well as QC figures on a webpage. Concerning SLR processing, the BKG contribution to ITRF2020 will be the overwhelming challenge for the reporting period to come. This especially implies to derive Etalon orbits covering the years 1993-1999 as well as to include LARES as a fifth satellite, and to estimate low-degree gravity field coefficients (see Sośnica et al., 2015 and Meyer et al., 2019).

Apart from the operational ILRS-AC activities, BKG is supporting the development of SLR data analysis capacities in Latin America. This cooperation with the SIRGAS community has been established in 2017 with a first workshop on SLR in Latin America. Several lectures about SLR, ILRS and global reference frame were given by Daniela Thaller within the SIRGAS 2017 Symposia held in Mendoza (Argentina):

http://www.sirgas.org/fileadmin/docs/Boletines/Bol22/SIRGAS2017_Report.pdf

As a follow-up activity, a second SLR Workshop in Latin America was organized in conjunction with the SIRGAS 2019 Symposia held in Rio de Janeiro (Brazil). Up to 25 participants from eight countries attended this 3-day workshop with an intense program of introductory lectures and exercises on SLR data handling and SLR data analysis using the Bernese GNSS Software version 5.2:

http://www.sirgas.org/fileadmin/docs/Boletines/Bol24/Symposium_SIRGAS2019_summary.pdf

BKG will continue to support the SIRGAS community with their efforts to establish SLR data analysis capacities in Latin American countries.

Figures 7-5: The second SIRGAS SLR Workshop held at IBGE (Instituto Brasileiro de Geografia e Estatística), Rio de Janeiro (Brazil), November 6-8, 2019, with exercises on SLR data processing using the Bernese GNSS Software.

AC Personnel

- Dr. Daniela Thaller, Head of unit
- Dr. Daniel Koenig, responsible for operations

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Meyer, U., K. Sośnica, D. Arnold, C. Dahle, D. Thaller, R. Dach, A. Jäggi (2019): SLR, GRACE and SWARM Gravity Field Determination and Combination. Remote Sens. 2019, 11, 956. Doi: 10.3390/rs11080956

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

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Thaller, D., K. Sośnica, R. Dach, A. Jäggi, G. Beutler (2012): LAGEOS-ETALON solutions using the Bernese Software. Mitteilungen des Bundesamtes fuer Kartographie und Geodäsie Band 48, "Proceedings of the 17th International Workshop on Laser Ranging, Extending the Range", May 16-20, 2011 Bad Kötzting, Germany; vol. 48, pp. 333-336; ISSN 1436-3445; ISBN 978-3-89888-999-5

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Areas of Interest

The ILRS AC at Deutsches Geodätisches Forschungsinstitut- Technische Universität München (DGFI-TUM) contributes to all ILRS Analysis Standing Committee (ASC) routine station coordinate and Earth orientation parameter products named “v170” (daily-shifted 7-day loose-constrained solution) and “v70” (weekly-shifted 7-day loose-constrained solution). These solutions are based on the analysis of SLR observations to the spherical geodetic satellites LAGEOS-1/-2 and Etalon-1/-2 downloaded from the Eurolas Data Center (EDC). The EDC is, in addition to the ILRS AC, also hosted at DGFI-TUM together with the ILRS Operation Center under the supervision of M.Sc. Christian Schwatke. Moreover, DGFI-TUM provides reduced-dynamic orbit solutions of the prior mentioned satellites in the SP3c file format with a 60 second and 120 second temporal resolution, respectively.

In addition to the routine contributions to the ILRS ASC which are submitted to the ILRS Combination Centers hosted at ASI (Italy) and NASA GSFC/UMBC (Maryland, USA), DGFI-TUM also provides input to the ILRS ASC pilot projects such as the “v230” project on systematic errors of ILRS ground stations. DGFI-TUM also evaluates the impact of the station-dependent SLR time biases derived from the T2L2 experiment.

Besides the ILRS ASC contributions, DGFI-TUM routinely computes 7-day orbit solutions of the Low Earth-Orbiting (LEO) satellites LARES, Larets, Ajisai, Stella and Starlette. Based on these observations, an SLR constellation solution for the TRF, the EOP and Earth’s gravity field coefficients is routinely computed (Bloßfeld et al., 2016b, Bloßfeld et al., 2018a). An important role also plays the combination of GRACE and SLR NEQs for the consistent estimation of low and high degree time-variable Stokes coefficients (Haberkorn et al., 2016). In the past, also the whole mission periods of GFZ-1, Westpac and the Russian BLITS satellite were analyzed. Relatively new is the analysis of SLR observations to non-spherical satellites such as the Jason satellites. Up to now, the whole mission periods of Jason-1, Jason-2 and Jason-3 have been processed.

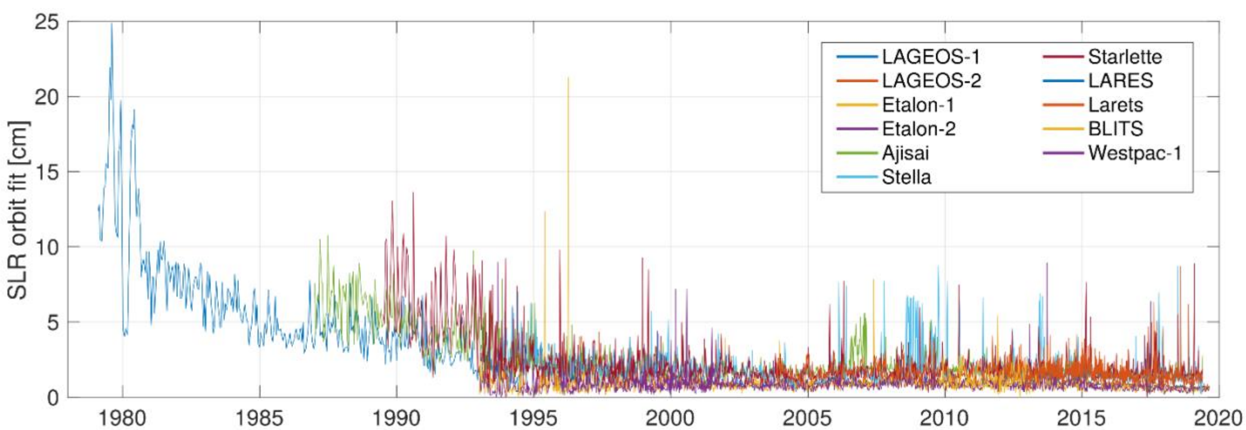

Figure 7-6: Arc-wise RMS of SLR observation residuals for multiple (non-)spherical satellites.

DGFI-TUM also contributes with SLR simulations to the standing committee on Performance Simulations and Architectural Trade-offs (PLATO) of the Global Geodetic Observing System (GGOS). Here, DGFI-TUM quantifies the impact of new SLR ground stations and improved quantitative performances of existing SLR ground stations on geodetic parameters.

AS a member of the ILRS Quality Control Board (QCB), DGFI-TUM tries to contribute to the preservation of the high quality SLR observations provided by the ILRS ground stations.

Finally, the DGFI-TUM SLR group published several SLR-related papers in the last years and gave numerous oral and poster presentations at different scientific conferences. A PhD thesis with the topic "*The key role of Satellite Laser Ranging towards the integrated estimation of geometry, rotation and gravitational field of the Earth*" was published in 2015.

Recent Progress and Analysis Center Improvements

In March 2018, Dipl.-Ing. Horst Müller retired after working nearly 40 years at DGFI-TUM. He was the head of the ILRS AC over multiple years, and significantly contributed to the development of the DGFI Orbit and Geodetic parameter estimation Software (DOGS). He originally designed the architecture of the routine processing operations at DGFI-TUM and served for many years as the primary network administrator at our institute.

Moreover, just 2 months before Horst Müller, Dr.-Ing. Michael Gerstl was also retired from DGFI-TUM. Dr. Gerstl was the primary developer of the DOGS software and helped many colleagues world-wide with his profound knowledge in mathematics and theoretic geodesy. Michael Gerstl worked from January 1981 for DGFI-TUM and is still active at our institute.

In the last years, the scope of our institute changed from the routine processing of SLR observations of the four main ILRS targets (LAGEOS-1/-2 and Etalon-1/-2) towards a long-period multi-satellite SLR processing. Up to now, we finished the orbit analysis of all spherical satellites which were and still are orbiting the Earth's. In total, 17 satellites are processed over their full mission period and might be incorporated, in the near future, into our multi-satellite SLR solution.

Since some years, DGFI-TUM computes SLR-based time-variable Earth's gravity fields (low-degree spherical harmonics up to degree and order 10) and provides them to scientific users world-wide (Bloßfeld et al., 2018b). Recently, DGFI-TUM also works on a multi-institutional SLR-based gravity field normal equation (NEQ) time series, where multiple institutions contribute to.

In the past three years, we use SLR observations to estimate thermospheric density scaling factors since spherical SLR satellites at very low altitudes (spherical satellites ANDE-C, ANDE-P and Spinsat) are very valuable to calibrate accelerometer-based thermospheric density models (Panzetta et al., 2018, Rudenko et al., 2018b, Xiong et al., 2018). During this analysis, also the processing of SLR observations to non-spherical satellites (primarily Jason-1/-2/-3 satellites) was implemented in DOGS together with the observation-based (satellite body quaternions and solar panel rotation angles) attitude handling. Moreover, the DOGS software is now capable to process DORIS observations. Up to now, the three Jason altimetry missions are reprocessed using SLR and DORIS observations.

At DGFI-TUM, SLR observations are also used for the joint estimation of the terrestrial and celestial reference frame in one common adjustment (Kwak et al., 2018). Therefore, SLR NEQs from DGFI-TUM are combined with NEQ from the other geodetic space techniques GNSS, VLBI and DORIS. Moreover, the most recent realizations of the TRF (ITRF2014, DTRF2014 and JTRF2014) are evaluated based on SLR analysis (Bloßfeld et al., 2018, Rudenko et al., 2018).

Technical Challenges and Future Plans

Over the next two years, the primary focus will be put on the further development of the DOGS software in order to finalize a common precise orbit determination (POD) based on SLR (and DORIS) observations. For this purpose, also other non-spherical satellites such as TOPEX/Poseidon, HY-2A/B, Sentinal-3A/B, Saral and Cryosat-2 will be implemented. Currently under investigation is the refined satellite attitude realization based on attitude observations (satellite body quaternions and solar panel orientation angles).

Another important topic will be the development of the parallel orbit integration in DOGS in order to be able to combine multiple satellites at the observation level of the Gauss-Markov adjustment model (currently combined at NEQ level) and to process inter-satellite links in the future.

Besides the ILRS AC, DGFI-TUM also operates an IERS ITRS Combination Centre. In the framework of the new ITRS realization computed in 2021 (ITRF2020), DGFI-TUM will extensively work on the analysis of the ILRS contribution to the ITRF2020 and also contribute as an ILRS AC to this solution. Therefore, LAGEOS-1/-2 and Etalon-1/-2 observations will be reprocessed between 1983 and 2021. In addition, alternative TRF products are investigated (Bloßfeld et al., 2016a).

Finally, DGFI-TUM will further work on the simulation of future ILRS networks and station performances within the framework of the GGOS PLATO group (Kehm et al., 2017, Männel et al., 2018). Moreover, several externally funded projects are planned which might offer the opportunity to do further research on the SLR techniques and its usability in up-to-date Earth's system research.

AC Personnel

- Dr.-Ing. Mathis Bloßfeld (ILRS AC head, member of ILRS QCB)
- Dipl.-Ing. Alexander Kehm (ILRS AC backup)
- M.Sc. Christian Schwatke (ILRS EDC/OC chair)

Figure 7-7: DGFI-TUM ILRS AC/DC personnel (left to right): M.Sc. Christian Schwatke, Dipl.-Ing. Alexander Kehm, Dr.-Ing. Mathis Bloßfeld) in front of the Mount Stromlo Observatory (Canberra, Australia).

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Areas of Interest

The navigation support office (OPS-GN) at the European Space Operations Centre (ESOC) of the European Space Agency (ESA) is active in all three international satellite geodesy services: the IDS, IGS, and ILRS. A unique feature of the ESOC participation in these three services is that its contributions to all three techniques are based on the same software, called NAPEOS.

ESOC has been a full analysis centre of the IGS since its beginning in 1991. In 2008 ESOC undertook a significant effort to become a full analysis centre also in the IDS and ILRS. As AC in the three techniques it also participated in the reprocessing efforts for the ITRF2008 and the ITRF2014 and is now also participating in the reprocessing for the ITRF2020 in all three services.

The participation in all three techniques is considered as a “first step”. Our ultimate goal is to do a fully combined analysis of the data of all three techniques, and in the future even 4 techniques when adding VLBI. In such a combined analysis the strength of each technique may be used to overcome the weaknesses in the other techniques. In this combination of techniques SLR plays a crucial role as it is the only technique that provides (more or less) unbiased range measurements. Furthermore, SLR is the only technique that provides direct access to the orientation and the scale of the terrestrial reference frame. In addition, SLR is extremely important in validating the orbits of both the IGS and the IDS.

Recent Progress and Analysis Center Improvements

In the pilot project for biases the ESOC bias solutions were clearly different from the other ACs. This was investigated and it was found to be caused by an erroneous setting of the troposphere correction. After this problem was resolved the biases became very similar to those of the other ACs. This troposphere bug also affected the routine solutions where after fixing it the scale of the solution changed noticeable and became in better agreement with the other ACs. In general, the quality of the ESOC ILRS contributions seems to be very good.

The space debris office of ESOC was looking for orbits of some of the other SLR cannonball targets as they use them as “calibration” targets. Since we start our processing with a 3-week pre-processing solution we decided to include these targets in this pre-processing step. The satellites we included are: LARES (to be included in the ILRS soon anyway), Ajisai, Stella, Starlette, and Larets.

Technical Challenges

In our GNSS work we always make use of the SLR observations of the GNSS satellites to validate our orbits and the models we are using. For example, we have performed an initial reprocessing of all the IGS data for ITRF2020 and analyzed the quality of the obtained solutions with all the available SLR data of the GNSS targets. Table 7-2 below summarizes the obtained statistics (based on one-way SLR observation residuals).

The table shows the very good agreement between the GNSS based orbits and the SLR observations. Only for Galileo a small mean is still visible. Thanks to the SLR observations we were able to identify this issue and also have the means to validate our solution(s) for it. Our latest results with an improved thermal model for the Galileo FOC satellites no longer show a significant mean offset.

Last but not least the table shows that we have over 1 million (!) of SLR observations with a sigma of around 20 mm which could contribute to the ITRF2020 if we would include them in a combined SLR-GNSS (re)processing. This would tie the SLR and GNSS sites not only through the ground co-location sites but would also tie them "in space". We believe that this would bring a significant benefit for both techniques!

Table 7-2. Quality of SLR solutions of GNSS targets

GNSS	Number of NPT	Mean (mm)	Sigma (mm)	Timeframe
GPS	108871	-4.9	21.5	1995-2020
GLONASS	856094	-1.7	23.7	2009-2020
Galileo	232393	16.9	17.6	2015-2020

Note that BeiDou and QZSS are not included in these statistics as they are not yet included in our IGS (re)processing.

Future Plans

We are currently in the final stages of developing the VLBI capabilities of our NAPEOS software. Ideally we would be able to participate in the ITRF2020 reprocessing for VLBI but that in not very likely at present. We are lacking some operational features to make that (easily) possible. But for the next ITRF (re)processing we are sure to be ready to contribute to all 4 techniques. And ideally we would also generate a "COOL" solution (COOL = Combination On the Observation Level) using all 4 techniques in one single solution.

Personnel

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Areas of Interest

Our main focus is to measure the shape and rotation of the Earth, its orientation in space, its surface and its gravitational field. For that purpose, SLR data serve as one of the key observation types in the analysis. Particular interests lie in the prospects of SLR in defining the origin of the Terrestrial Reference Frame (TRF) and its scale together with VLBI. Also, the low degree gravity field and its variations in time are deduced where the time series of C(2,0) values is supplied in support of the GRACE-FO mission.

Therefore, GFZ contributes to the ILRS by running a SLR station in Potsdam and an AC in Oberpfaffenhofen. On a daily and weekly basis, the AC operationally provides weekly global SLR ground station coordinates and daily EOPs from the analysis of SLR observations to the LAGEOS, LAGEOS-2, Etalon-1 and Etalon-2 satellites. On a weekly basis, also the orbits of these satellites are provided. Every few years the AC contributes to the development of the ITRF. The AC also takes part in the pilot projects and in other activities of the ILRS ASC, actually the pilot project "Systematic Station Error Monitoring" (SSEM) is being conducted.

Recent Progress and Analysis Center Improvements

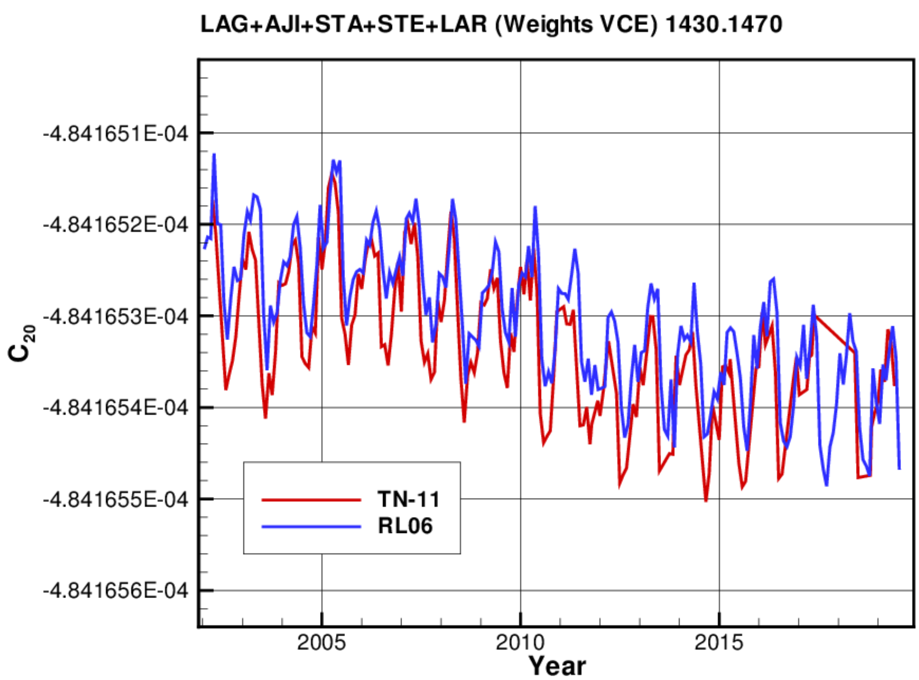

Figure 7-8. The GFZ C(2,0) time series (RL06) versus GRACE Technical Note 11 (TN-11).

In the reporting period the GFZ C(2,0) time series (König et al., 2019[1]) in support of the GRACE and GRACE-FO missions became published, it is maintained online and accessible through the GravIS portal[2]. The solution, fully compatible with GFZ's GRACE products, is constructed from SLR range observations to the

[1] König R, Schreiner P, Dahle C: Monthly estimates of C(2,0) generated by GFZ from SLR satellites based on GFZ GRACE/GRACE-FO RL06 background models. V. 1.0. GFZ Data Services, http://doi.org/10.5880/-GFZ.GRAVIS_06_C20_SLR

[2] gravis.gfz-potsdam.de

six geodetic satellites LAGEOS and LAGEOS-2 (spinning off from the AC's operational products), Ajisai, Starlette, Stella, and LARES. The contributions of the individual satellites are combined via variance component estimation. The result is in good agreement with the C(2,0) time series by the GRACE project published in Technical Note 11 as shown in Figure 7-8.

A major focus in the reporting period has been laid on analyzing via simulations the improvement of the terrestrial reference frame by extension of the ground station network and by combination with other space-geodetic techniques and space-geodetic missions. Also, the role of the local ties is studied in detail. The project named GGOS-SIM resulted in a powerful software tool and an impressing ensemble of papers published[3].

Also, in the reporting period we found an operational procedure to include the Etalon satellites in the generation of the AC products. This migration provides a slight improvement of the EOPs, an example is shown in Figure 7-9. For the pilot project SSEM and for future re-processing efforts, the Etalon orbits have been processed back to the year 1993.

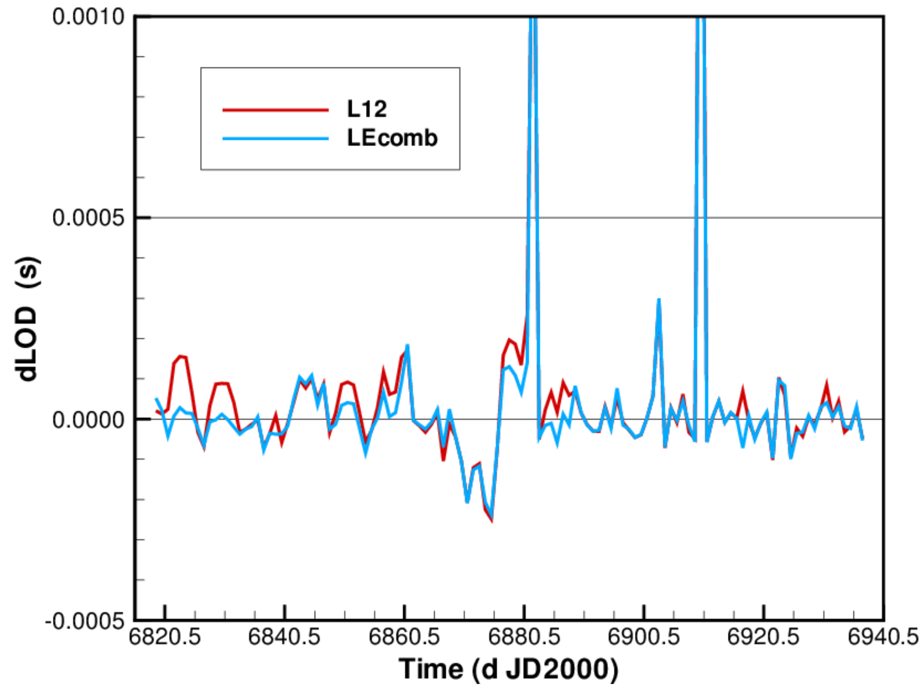

Figure 7-9. Improvement of the LOD estimates (the blue curve is closer to zero) if the Etalon observations are added.

Further, our software has been updated to handle the new linear mean pole convention, the new wavelength dependent center-of-mass corrections for SLR range observations and the new high frequency Earth orientation parameter model. The CRD V2 format is under testing. Our local data archive has been updated, cleaned and prepared for newly released historical data by some stations.

Technical Challenges and Future Plans

The next two years will see the incorporation of the LARES observations into the operational AC products. Also, the augmentation of the AC product list by low degree gravity field parameters will play a major role. Above this, we will focus on the optimal combination of all space geodetic techniques for improved monitoring of the Earth's shape and orientation in space and it's time variable gravity field.

[3] https://www.earth.tu-berlin.de/menue/forschung/laufende_projekte/ggos_sim/parameter/en/

AC Personnel

- Dr. Rolf König, head, development, AC operations
- Margarita Vei, AC operations, maintenance
- Ingo Meyer, hardware
- Dr. Hans Karl Neumayer, mathematics, software
- Patrick Schreiner, testing, AC operations back up
- Dr. Krzysztof Snopek, data acquisition, archive

Figure 7-10. The team from left to right: P Schreiner, I Meyer, M Vei, K Snopek, HK Neumayer, R König.

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GRGS (Groupe de Recherche de Géodésie Spatiale), France

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Areas of Interest

Fields of interest at the GRGS include:

- Earth rotation, and its gravity field
- Terrestrial reference frame: station coordinates, Helmert transformation
- Orbit determination and validation

Operational activities: ILRS weekly/daily products: Solutions (orbits + inversion of stacked normal equations) computed on a weekly basis. SINEX files contain EOP (A set per day) and station coordinates (1 set per week). Based on data acquired by the ILRS network on LAGEOS-1 and -2, Etalon-1 and -2 (LARES currently being tested as a future satellite included in the operational products).

Recent Progress and Analysis Center Improvements

The GRGS has been the analysis center of the International Laser Ranging Service since 2008. In 2012, following the transfer of Florent Deleflie from the OCA to the Paris Observatory, and the return to Paris of David Coulot (IGN), the operational SLR processing chains based on GINS/MATLO software, then GINS/LOCOMOTIV are installed on the servers of the Institut de Mécanique Céleste et de Calcul des Éphémérides, on the Paris site of the Paris Observatory. The period 2016-2018 was particularly difficult due to an extremely significant breakdown of the IT resources of the IMCCE which has had a strong impact on the activity of the analysis center since the middle of 2016. A significant part of the time allocated to the tasks of Florent Deleflie was devoted over the period to the re-establishment of an operational IT architecture for the Analysis center, with a backup of the scripts and results now managed directly by the project leaders. In parallel, a duplication of the processing chains is in the implementation phase within the IGN and the CNES to (i) avoid in the future that such events occur again, (ii) bring together the GRGS colleagues involved in the project, using the most up-to-date tools (including GINS) developed in Toulouse and Paris.

From an operational point of view, the situation of the analysis center is now as follows:

- The processing chains installed at the IMCCE are operational, and the period 2017-2018 has been processed; this concerns the four satellites used by ILRS for operational analyses (LAGEOS-1, LAGEOS-2, Etalon-1, Etalon-2).
- The processing now takes place on a server fully allocated to SLR processing (in particular thanks to funding obtained from CNES in 2017), and a clear policy distinguishing backups between production directories and modeling directories has been defined; today it's highly unlikely that a situation like the one we experienced in 2016 will ever happen again.
- The processing chain is entirely duplicated at IGN-LAREG.

Technical Challenges

The evolution of modeling is at the heart of our research, with the aim of achieving ever better precision and accuracy for the next products delivered by ILRS:

- The determination of biases in distance, and their temporal variability according to the technological evolutions of the stations, is at the heart of this research. In parallel with the

activities carried out within the ASC, we compared the results obtained by several methods of determination of the biases;
- From the point of view of the search for a better orbitography, an important work was carried out to evaluate the performances of the albedo models already old used in operational calculations; an update of these models has been the subject of several presentations, and this new model built at IMCCE is in the final phase of evaluation before its publication;
- In the same spirit, an in-depth study of the influence of solar events on variations in atmospheric density used, on the one hand, the SLR data processed at the IMCCE, in addition to the accelerometric data from GRACE;
- And we should also mention the work on the modeling of the attitude of the satellites, compared with "full-rate" data obtained by the best kHz stations.

At the same time, research activities that do not depend directly on the operational nature of the analysis center continued. We can cite in particular the end of a new phase of T2L2 data processing. However, due to IT difficulties at the IMCCE, which was recently completed, it was not possible in 2018 to play a central role in identifying all the studies using SLR data;

Future Plans

We now have to show our ability to participate again in all of ASC activities from 2019. This includes:

- The installation in 2020 of a new GRGS service making it possible to detect “jumps” in the distance biases of the network stations, and independently (therefore with an adapted analysis scheme) of the operational solution. This responds to a greater need than in the past for interaction between (French) observers and (French) analysts;
- The inclusion of a fifth satellite, LARES, in the list of satellites whose trajectory is analyzed from an operational point of view; tests must now be extended to the entire period over which LARES data are available (2012);
- The preparation of the preliminary tests with a view to the future realization of the ILRS contribution to the ITRF2020: this includes the restarting of the historical data processing chain (since 1983);
- The improvement in the level of precision of the GRGS Etalon satellite orbits, three times worse on average, for a reason not yet identified, than the LAGEOS orbits, while the other analysis centers do not observe this degradation (even if this proportionally concerns only an extremely small number of data).

Future plans: contribute again as a regular and reliable basis to the ILRS.

1. Contributing with an operational mode again: SP3c orbits of the geodetic satellite constellation, + snx files with EOP and SSCs
2. Contributing again to Pilots Projects of the ASC
3. Return to a full nominal mode as an official ILRS AC hosted @ Paris Obs

Planned developments :

- Solutions based as well as other geodetic satellites
- Optimization of the combination between different dynamical configurations
- Time series of degree 2 gravity field coefficients, on an operational point of view...
- Methodological activities concerning orbit modelling (non gravitational forces), range bias determination :(optimization of the decorrelation between estimated parameters),

AC Personnel

Figure 7-11. GRGS AC personnel (left to right): Florent Deleflie, Arnaud Pollet

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Areas of Interest

The JCET/GSFC AC is presently the coordinating AC for the activities of the ILRS ASC. JCET participated in all ASC-related ILRS activities during the period 2016-19. Our group focuses primarily on the analysis of SLR data from geodetic targets (e.g., the two LAGEOS, Etalons and LARES), to support the official ILRS products contributing to the IERS and ITRS.

Of equal importance though is our interest in controlling the quality of the tracking data and the official products. In that vein we run a quality control (QC) series on a daily basis and deliver online a report that characterizes on a pass-by-pass basis the data quality of all active tracking stations. The results, along with those from similar analyses at other ILRS ACs are available online for further examination and visualization over time, through our "QC Report" web portal (*http://geodesy.jcet.umbc.edu/ILRS_AWG_MONITORING/*). Additional tools, recently developed, will be described in the next section. JCET has a prime interest in the expansion of the geodetic constellation and this was first demonstrated with the joint proposal, design and exploitation of the LARES mission launched in 2012. Our collaboration with the Italian teams at Univ. of Roma "Sapienza", the Univ. of Salento and ASI (Agenzia Spaziale Italiana) resulted in a second accepted proposal for another mission, LARES-2, with a launch date set in the fall of 2020.

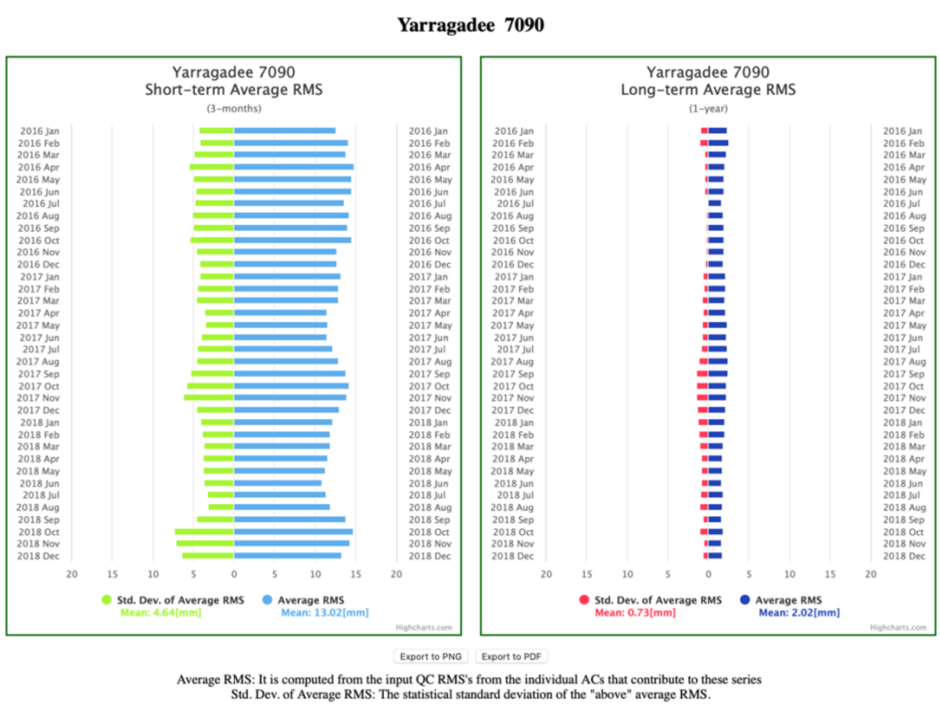

Figure 7-12. A visual display of Yarragadee's (7090) short-term and long-term performance from the corresponding Monthly Report Cards published in the ILRS website (https://ilrs.gsfc.nasa.gov/network/system_performance/global_report_cards/monthly/).

Recent Progress and Analysis Center Improvements

There has been a lot of activity since our last published report (ILRS AR 2009-2010) and given the fact a significant time elapsed between that and the current report, we have decided to provide the state of things as of now rather than at the end of 2019. This we hope will minimize the confusion between what readers will read about as accomplishments of that 4-year period and the information available online today.

During the reporting period, the most significant item that all ACs had worked on was the change in the approach the ASC handled systematic errors in the network. Over these four years a new approach was tested and perfected with numerous repetitions of a complete reanalysis of the SLR data from 1993 to date. During this time, JCET has also developed and implemented several modeling improvements in order to enhance the quality of the operational products of ILRS under the umbrella of the newly established "Quality Control Board—QCB" of the ILRS. One of these is the establishment of a data base with the complete set of ILRS Report Cards (Monthly and Quarterly) with the capability to visualize the results for a specific station over a selected time period (Figure 7-12) on our "ILRS Report Card" web portal (*http://geodesy.jcet.umbc.edu/ILRS_REPORT_CARD/index.php*).This allows to monitor the stability of the system through the average RMS from the contributing ACs and the agreement of these ACs via the Standard Deviation for each month.

MONITORING SYSTEMATIC ERRORS AT ILRS STATIONS

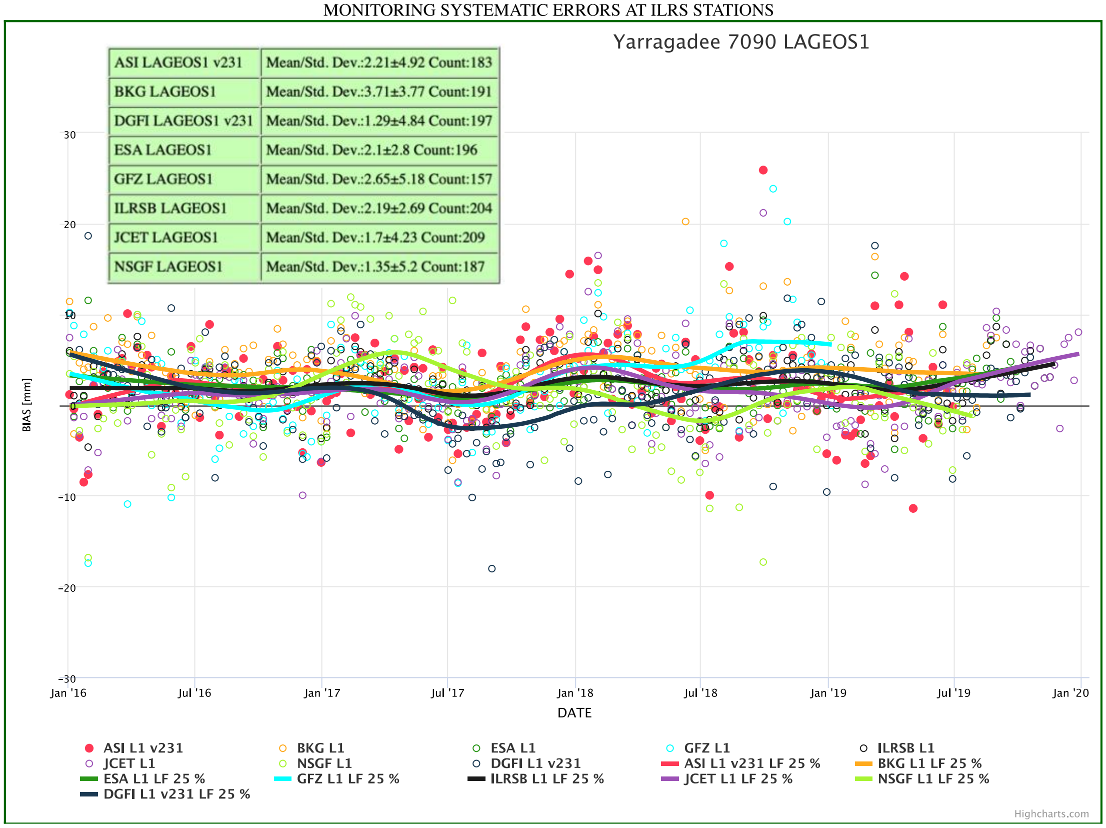

Figure 7-13. A visual display of SSEM PP results for Yarragadee (7090) on LAGEOS over the period 2016-2019 from the seven contributing ACs and preliminary ILRS-B combination.

With the newly adopted approach in Station Systematic Error Monitoring—SSEM Pilot Project—PP came the need to be able to quickly examine compared results between the contributing ACs and CCs. We stablished a data base with the results from each cycle of analysis, including the combined series, which can be visualized for any group or single AC and over any period of time specified at *http://geodesy.jcet.umbc.edu/BIAS_v230_EDIT/*, to obtain a graphic with the individual weekly estimates and a smoothed curve for each of the contributing ACs (Figure 7-13). The JCET portal continues to provide access to previously established functions, e.g., the evaluation of the weekly and daily ASC products, that now include a concise table which encapsulates the results of the daily analysis of the previous 7-days' data, in terms of the highest number of collected NPs, the lowest noise level in the data and a JCET-established metric for scoring the system performance: the "JCET Uniformly Independent Classification Entry—JUICE" score (Table 7-3). This index rewards systems with low noise and high yield, the characteristics that matter the most in developing high quality products.

Table 7-3: Daily summary of the active ILRS stations tracking the two LAGEOS and two Etalons.

JCET AC Station Performance Metrics for Arc: 200324

JUICE: JCET Uniformly Independent Classification Entry Score

SITENAME	SITE_NUM	AVG	STD	NPTS	SITENAME	SITE_NUM	AVG	STD	NPTS	SITENAME	SITE_NUM	JUICE Score
Zimm@532	78106821	0.1	6.5	551	Shangha	78212801	-0.0	1.9	15	Herstmon	78403501	102.232
Herstmon	78403501	-0.0	5.1	524	Hartebee	75010602	0.0	4.7	16	Zimm@532	78106821	85.358
Wettzell	88341001	-0.0	6.2	353	Herstmon	78403501	-0.0	5.1	524	Wettzell	88341001	56.712
Potsdam	78418701	-0.0	6.3	319	Matera	79417701	-0.0	5.9	57	Potsdam	78418701	50.514
WTZL SOS	78272201	-0.0	9.9	179	Wettzell	88341001	-0.0	6.2	353	WTZL SOS	78272201	18.050
Greenbel	71050725	-0.0	7.5	63	Potsdam	78418701	-0.0	6.3	319	Matera	79417701	9.605
Riga	18844401	-0.0	14.3	61	Zimm@532	78106821	0.1	6.5	551	Greenbel	71050725	8.420
Matera	79417701	-0.0	5.9	57	Monumen	71100412	-0.0	7.3	49	Shangha	78212801	7.776
Changch	72371901	-0.5	15.8	52	Haleakal	71191402	-0.0	7.3	39	Monumen	71100412	6.750
Monumen	71100412	-0.0	7.3	49	Greenbel	71050725	-0.0	7.5	63	Haleakal	71191402	5.338
Simosat	78383603	-0.0	12.8	48	Beijing	72496102	-0.0	8.2	23	Mendele	18748301	4.663
Mendele	18748301	0.0	10.1	47	Altay	18799401	-0.0	9.7	13	Riga	18844401	4.260
Haleakal	71191402	-0.0	7.3	39	WTZL SOS	78272201	-0.0	9.9	179	Simosat	78383603	3.736
Kunmin2	78198201	0.0	14.0	34	Mendele	18748301	0.0	10.1	47	Hartebee	75010602	3.380
HartRUSL	75036401	0.0	11.3	32	Komsomol	18685901	-0.0	11.0	16	Changch	72371901	3.283
Beijing	72496102	-0.0	8.2	23	HartRUSL	75036401	0.0	11.3	32	HartRUSL	75036401	2.826
Baikonur	18879701	-0.0	19.6	22	Simosat	78383603	-0.0	12.8	48	Beijing	72496102	2.813
Komsomol	18685901	-0.0	11.0	16	Kunmin2	78198201	0.0	14.0	34	Kunmin2	78198201	2.429
Hartebee	75010602	0.0	4.7	16	Riga	18844401	-0.0	14.3	61	Komsomol	18685901	1.451
Shangha	78212801	-0.0	1.9	15	Changch	72371901	-0.5	15.8	52	Altay	18799401	1.341
Altay	18799401	-0.0	9.7	13	Baikonur	18879701	-0.0	19.6	22	Baikonur	18879701	1.123

Technical Challenges

During the period 2016-2019 the ILRS ASC co-chairs undertook the editorship of a special issue of the Journal of Geodesy dedicated to Laser Ranging. Due to the great interest in the community to publish their work in such an issue, the editorial board was expanded to include two additional members so that the heavy load of the review process could be handled efficiently. The work was to be completed before the end of 2018, however, with several manuscripts still in the review process, an extension till the end of February 2019 was unavoidable. The twenty accepted articles were published online throughout the review process, the finished issue however was physically published in November 2019 [Pavlis, Luceri, Otsubo and Schreiber (eds.), 2019]. This is the second special issue on Laser Ranging, twenty years after the previous one published in 2001.

After receiving from ITRS the call for participation for the development of ITRF2020 in late 2018, we started planning the steps to be followed by the ILRS ASC, based on a timeline that expects the final contribution from all participating IAG Services by the end of February 2021. The challenges we are facing are several, the most important being the successful completion of the SSEM PP since the results will be used for ITRF2020 development. Additionally, we must incorporate the LARES data in the new model, a process that requires increasing the complication of our modeling due to its lower orbital altitude and higher sensitivity to gravitational perturbations. A PP was planned to ensure that all ACs are contributing consistent solutions of comparable accuracy. As a necessary by-product, the ASC will also deliver a weekly-averaged set of low-degree spherical harmonics of the static gravitational field.

Our AC is responsible for the validation and qualification of new SLR systems or existing ones that return to operations after significant down times for various reasons. As the ILRS community is deploying new systems at increasingly faster pace and placing systems in quarantine after more frequent upgrades and modernization, we are facing a task that will require increasing effort and resources. One possible solution is the use of data from additional targets, beyond those contributing to ITRF, to speed up the period of testing. This will require extension of our analysis series to include these low-altitude orbits that require more specialized modeling. We are currently investigating the automation of such analyses on a regular basis.

Future Plans

Based on the ASC plan for participation in the development of ITRF2020, next year (2020) will be devoted in the finalization of the SSEM PP model following the implementation of a new model for the target signature of the geodetic spheres, tailored to each of the active ILRS systems. The need for this improvement became evident after the initial results of the SSEM PP, where it was very clear that the freely estimated biases of the most prolific systems were systematically positive. At this time (early 2020), the implementation of a revised model released in November 2019 resulted in a much more random behavior of the systematics and an overall diminishing of the magnitude of individual stations' biases.

In the coming year the new approach developed under the SSEM PP will become the standard approach in the development of our official products which will require the development of an automated procedure in detecting significant changes in the long-term systematics of each active station in the ILRS network. We have been testing various possibilities and we will implement the one that yields the most reliable results in order to minimize the "false alarms" which can cause confusion in the analysis and undue mitigation efforts at the affected stations. Once we have detected systematics that the stations cannot rationalize and correct, we will include them along with their statistics in the new public version of the ILRS Data Handling file, for users to consider.

The U.S. Naval Observatory hosts IERS' Rapid Service/Prediction Center (RS/PC) for Earth Orientation (NEOS), that in turn uses the ILRS ASC daily EOP products in their forecasting algorithm. They have always required an EOP product that is available as soon as possible and with as high accuracy as possible. We are planning to initiate a series that will include as many SLR targets from LEO to GNSS altitude, to generate such a product on a regular basis. Initial tests with increased Etalon tracking during a 3-month campaign, indicated that this is a viable approach. We are looking at organizing a PP for this service sometime in 2020.

AC Personnel

Figure 7-14. JCET/GSFC AC personnel (left to right): Erricos Pavlis, Magdalena Kuzmicz-Cieslak, and Keith Evans.

Prof. Dr. Erricos C. Pavlis (AC head and ILRS ASC co-chair, member ILRS CB, GB, QCB and MSC), Dr. Magdalena Kuzmicz-Cieslak (AC and ASC member, in charge of daily/weekly data analysis and webmaster), and Mr. Keith Evans (AC and ASC member, in charge of daily/weekly combination of AC solutions and data base management and maintenance).

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NSGF (NERC Space Geodesy Facility), UK

Authors: *José Rodríguez, Graham Appleby*
Responsible Agency: British Geological Survey

Areas of Interest

As required from all official ILRS ACs, NSGF provides orbital dynamics solutions (daily and weekly series), estimating station coordinates at mid-arc epochs, daily EOP (pole coordinates and length of day), dynamic parameters and state vectors. The results are generated in SINEX format and uploaded daily to the two ILRS data centers. Additionally, orbit predictions for a range of satellites tracked by the ILRS network are provided as a backup service to the community.

Beyond the delivery of routine products, NSGF has been involved in two main areas: a) research on the identification and mitigation of systematic errors in the SLR technique; b) the determination of centre of mass corrections (CoM) for SLR geodetic satellites. As a result of these efforts, NSGF has made significant contributions in the field of SLR analysis: prompting the ILRS Analysis Standing Committee to develop a new product based on the estimation of systematic errors along with station coordinates; providing newly computed CoM values for all stations of the network based on models we developed. Results relating to these areas have been published, presented at numerous venues, and made available to the community.

Key results:

- Systematic errors in the SLR technique are responsible for ~50% of the scale difference between the VLBI and SLR networks (~1.37 ppb in ITRF2014)
- Estimation of range biases simultaneously with coordinates for all stations of the network is feasible and offers a bias-free product (long-term, accuracy/noise trade-off)
- Pilot Project on systematic errors prompted from these results nearing completion in 2019 (initial plan devised by NSGF and DGFI). It will be the basis for the ILRS reanalysis for the next realization of the ITRF (planned for 2020)
- New/updated models developed for the computation of CoM offsets for geodetic satellites Starlette, LAGEOS-1/2, Ajisai, Etalon-1/2, and LARES
- Models take into account more aspects of the laser ranging measurement than ever before, modeling explicitly for the first time, stations operating at the multi-photon level of detection
- CoM inaccuracies responsible for some of the range biases estimated for many tracking stations
- New estimation of the geocentric gravitational constant, GM, using state of the art modelling including newest CoM values, agrees with currently established standard with much reduced statistical uncertainty
- New CoM values computed for all stations of the network whose coordinates contribute to the ITRF since 1983. Software provided to interrogate the tables

Recent Progress and Analysis Center Improvements

The software employed to provide routine products has been migrated to the setup employed for the generation of the reanalysis for ITRF2014. This branch was developed in parallel to the stable one, and received many updates to modernize parts of the code, to implement new or more up-to-date models as required, and to introduce new features as these were developed. The code used for the routine products is kept in a frozen state, only receiving updates when strictly necessary (e.g., bugfixes), or when changes do not affect the daily/weekly results (e.g., unrelated features to these solution types). The development version is continuously updated to meet the requirements of the various pilot projects planned within the ILRS ASC, as well as for research purposes.

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AC Personnel

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- José Rodríguez (at Yebes Observatory, Spain, since 2020)

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ILRS Combination Centers

ILRS Combination Centers retrieve the solution files produced by the ILRS Analysis Centers, using them as input to produce the official, and final, ILRS combined products (station positions, velocities, EOP, and orbits). These solutions are designated “ILRS A”, produced by the ILRS primary combination center (Italian Space Agency/ASI, Matera, Italy), and “ILRS B”, produced by the ILRS backup combination center (NASA GSFC/University of Maryland Baltimore County (UMBC) Joint Center for Earth Systems Technology (JCET), Greenbelt MD, USA).

Table 7-4. ILRS Combination Centers (CCs)

Code	AC Title and Supporting Agency
ILRSA	ILRS primary Combination Center, Italian Space Agency, Centro di Geodesia Spaziale "G. Colombo" (ASI/CGS), Italy
ILRSB	ILRS backup Combination Center, Joint Center for Earth Systems Technology/Goddard Space Flight Center (JCET/GSFC), USA

ASI/CGS (Agenzia Spaziale Italiana, Centro di Geodesia Spaziale "G. Colombo") ILRS Primary Combination Center

Authors: *G. Bianco (ASI), V. Luceri (e-GEOS S.p.A.)*
Responsible Agency: Italian Space Agency/Space Geodesy Center "G. Colombo"

Areas of Interest

The ASI Space Geodesy Center "G. Colombo" (ASI/CGS) is the Primary ILRS Combination Center since 2004 when it was selected for the combination of the ILRS products, currently: station coordinates, Earth Orientation Parameters, satellite orbits, station range biases. ASI/CGS is a Fundamental Station of the geodetic network, hosting three permanent Space Geodetic systems (SLR, VLBI, GNSS, absolute gravimeter) and, due to the multi-technique nature of the CGS mission, space geodetic technique combination methods and applications are a top priority objective of the data analysis activities. Besides the single-technique data analysis as Analysis Center (AC), ASI/CGS is involved in combination activities aiming to provide specific products and as well as to test combination methodologies.

The ILRS combined solutions for coordinates and EOPs are obtained using the SW COGEOS developed internally and routinely maintained in order to address the requirements of the ILRS Analysis Standing Committee (ASC). The combination methodology relies on the direct combination of loosely constrained solutions; this straightforward method (e.g., "Methodology for global geodetic time series estimation: A new tool for geodynamics", P. Davies and G. Blewitt, JGR, vol. 105, no. B5, pages 11083–11100, May 10, 2000) allows handling input solutions easily. The reference frame is defined stochastically and is unknown; no relative rotation between the reference frames is estimated and removed.

Information on the CGS and some of the analysis results are available at the CGS website GeoDAF (Geodetic Data Archiving Facility, *http://geodaf.mt.asi.it*).

Recent Progress and Analysis Center Improvements

In the 4 years 2016-2019, the ASI/CGS has been deeply involved in the ILRS activities, mainly in support of the reference frame maintenance and under the coordination of the ILRS ASC. The ASI CC contributions as ILRS Combination Center are listed hereafter:

- ILRS Routine Products:
  - daily submission of the ILRS official solution (ILRSA) computed using the individual AC parameter estimates based on the analysis of observations to LAGEOS-1, -2 and Etalon-1, -2 satellites over a 7-day arc. The ILRSA solutions contain weekly coordinates of the worldwide SLR tracking network and daily EOPs (x-pole, y-pole, LOD) and it is loosely constrained. A separate daily EOP product is derived from the previous one and constrained to ITRF, it is the ILRS contribution to EOPC04.
  - weekly submission of the combined coordinate/EOP solutions computed using the individual AC contribution based on the observations to LAGEOS-1, -2 and Etalon-1, -2 satellites. This product is similar to the daily official product but has a larger latency and is often used as benchmark.
  - weekly orbits obtained combining the state vectors of the four satellites, LAGEOS and Etalon, estimated by the ILRS ACs. They are available in the ITRF reference frame.
  - Periodic evaluation of the submitted official products are presented at the ILRS ASC meetings to support ACs data analysis activities. The CC is always ready to support the ACs whenever anomalies arise in the submitted solutions or new models are implemented.
  - Geocenter motion: the ILRS SLR time series plays a fundamental role in the definition of the ITRF origin. The geocenter motion is routinely computed applying the Helmert transformation

from the loosely constrained solutions to the ITRF. The figure below is an example of the X translation to ITRF2014.

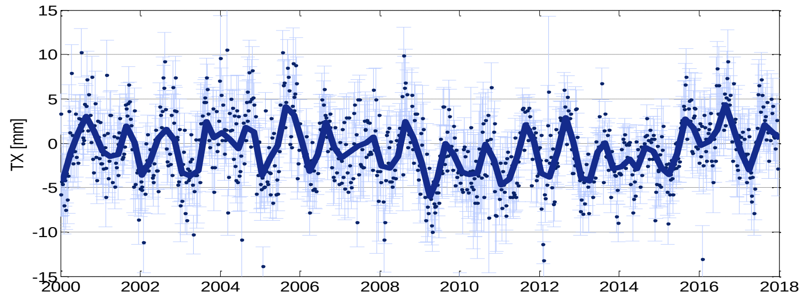

Figure 7-15. X component of the geocenter motion.

- IITRF realization
  The ILRS CC has a fundamental role in the realization of a new ITRF. It is in charge of the delivery of the official ILRS contribution to the reference frame and works on the verification of the ITRF once it is delivered. ITRF2014 was delivered at the beginning of 2016 and tests were performed before adopting the ITRF in the official products mostly due to the implementation of the new post seismic deformation model. Preparation of the next ITRF2020 is underway.
- ILRS Systematic error Pilot Project
  The ILRS ASC established in 2016 a pilot project on the station systematic errors with the aim to recover potential bias directly from the data. The single AC solutions, now including site coordinates, EOP and biases, were combined to obtain a time series of range bias for each single station. The SW COGEOS was modified to include the new parameters into a rigorous combination process. The pilot project proved that this analysis strategy can recover real biases and the agreement among the ACs is generally within the uncertainty of the estimates, except in a few cases usually involving stations with poor or sparse data records. The impact of the approach on the reference frame was investigated by looking at the translations and scale of the loosely constrained combined time series with respect to ITRF2014. More details on the argument are described in the ASC report in this volume and in the paper "Systematic errors in SLR data and their impact on the ILRS products" (V. Luceri et al.) of the special SLR issue Journal of Geodesy (2019).

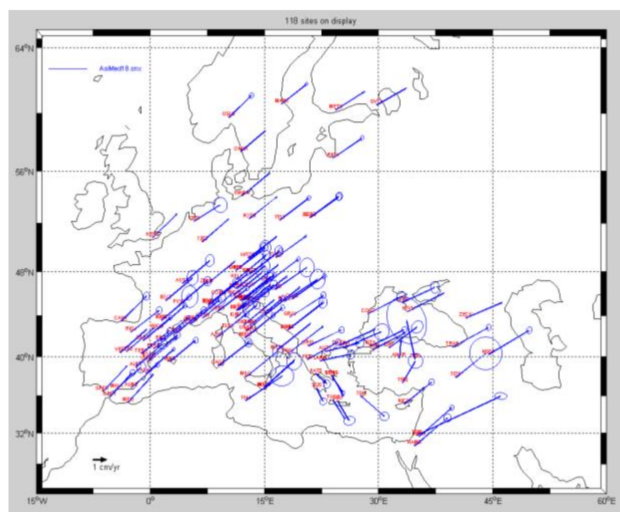

Figure 7-16. The ASIMed velocity field.

Moreover, ASI/CGS in involved in geodetic solution combination: realization, implementation and testing of combination algorithms for the optimal merging of global inter- and intra-technique solutions and of regional (e.g., Mediterranean) solutions to densify tectonic information in crucial areas.

Once a year, ASI/CGS produces a combined velocity solution for the Mediterranean area using its original single-technique velocity solutions (SLR, VLBI and GPS) that cover the whole data span acquired by the three co-located systems from the beginning of acquisitions in Matera. The ASIMed solution gives a detailed picture of the velocity field in the area, profiting of the dense permanent GPS coverage.

Technical Challenges and Future Plans

The next two years will be mainly focused in the preparation of ITRF2020. Work is already in progress and the first step will be the completion of the pilot project on station systematic errors. ASI/CGS is in charge to compute the output of the PP that will be a new error model, i.e., a new data handling file with the list of bias to be used by the ACs to prepare their solution time series.

After the conclusion of the PP, the ASI/CGS combination activities will continue with the evaluation of each loosely constrained solutions provided by the official ILRS ACs (ASI, BKG, DGFI, ESA, GFZ, GRGS, JCET, NSGF) and then their direct combination.

Some of the goals for the work to be done in the near future are the same of the ILRS ASC since all the new features in the solutions are new features to address in the combined product:

- Estimation of low-degree SH of the gravity field
- Inclusion of LARES as a 5th satellite in the operational product
- Plan for the expansion of the target used in operational products
- Pilot project on NT Atm. Loading and Gravity.

CC/AC/AAC/LAAC Personnel

The Italian Space Agency is the owner of the Space Geodesy Center and is the decision-making body, Giuseppe Bianco, director of the ASI/CGS, is the ASI manager of the Combination Center. The activities of the Combination Center are performed by e-GEOS S.p.A. (formerly Telespazio) since the very beginning in the 80's. The team is composed by six people involved in SLR, VLBI and GNSS data analysis. The SLR data analysis is coordinated by Vincenza Luceri.

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JCET/GSFC (Joint Center for Earth Systems Technology/Goddard Space Flight Center) ILRS Backup Combination Center (ILRSB)

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Responsible Agency: JCET/UMBC

Areas of Interest

JCET hosts the back-up ILRS Combination Center (CC) since December 2010. The purpose of the back-up CC is to ensure that there is always a combined product generated and available online; furthermore, the comparison of the official and back-up combinations can verify the quality and consistency of the ILRS products. Although both CCs use the same AC-provided solutions as input, the combination approach followed by each CC is independent and slightly different in practice. The official product ILRS-A uses directly the solution vectors from each AC product and through a weighted approach that is based on the AC-provided covariances, the combined solution ILRS-A is generated as their weighted mean. In contrast, the back-up combined solution ILRS-B is obtained from a formal Least Squares adjustment, where the input is the Normal Equations (NEQs) obtained from the loosely constrained covariances after their inversion and subtraction of the known loose *a priori* constraints. In both cases the weighting of the input solutions is based on Variance Component Estimation (VCE).

Over the period covered in this report the seven ACs that actively contributed to the ILRS combined products were: ASI, BKG, DGFI, ESA, GFZ, JCET and NSGF. In general, the contributions were received on time daily, as Figure 7-17 attests.

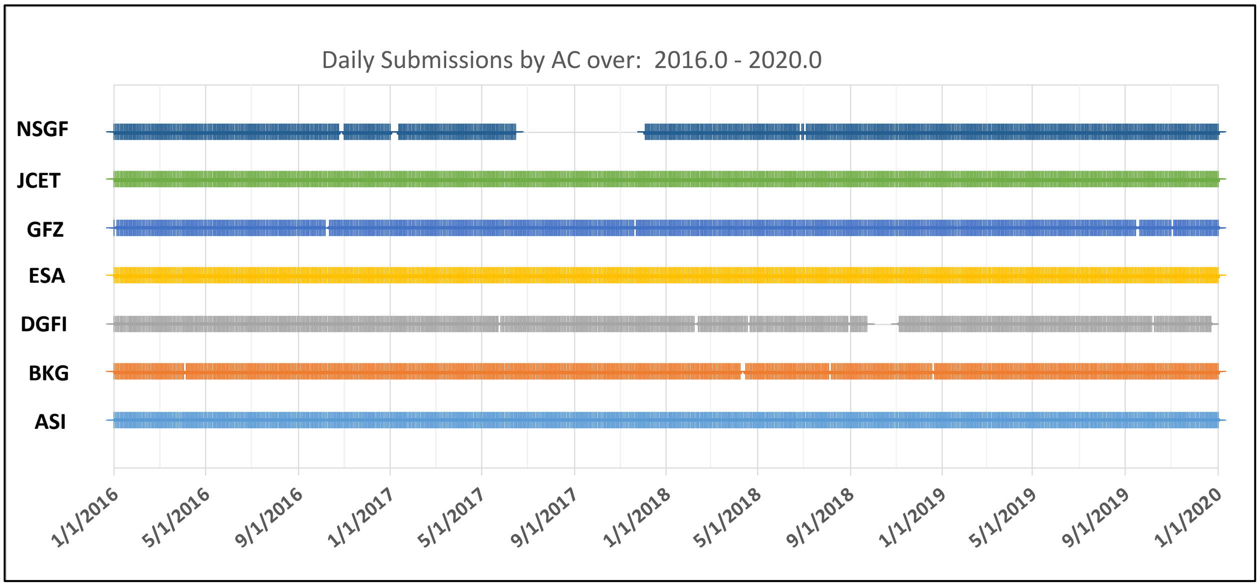

Figure 7-17. Record of the daily AC submissions to be combined at JCET CC over the reporting period.

The results of the ILRSB combination (as well as those of the official ILRSA combination) are uploaded daily online for further examination and intercomparison via our JCET Portal (*http://geodesy.jcet.umbc.edu/ILRS_AWG_MONITORING/*). If you select the 1st option "Weekly Station Positions & Daily EOP Series", then you can access and graph the evolution of any station's position component in Cartesian or local coordinates from ITRF2014/SLRF2014 and the daily EOP offsets from IERS Bulletin A series. Selecting the 3rd option "Evaluation of Weekly ASC Products" you can access and graph the results of the official (Daily) and previous version (Weekly) combinations, including the individual AC contributions to these combinations.

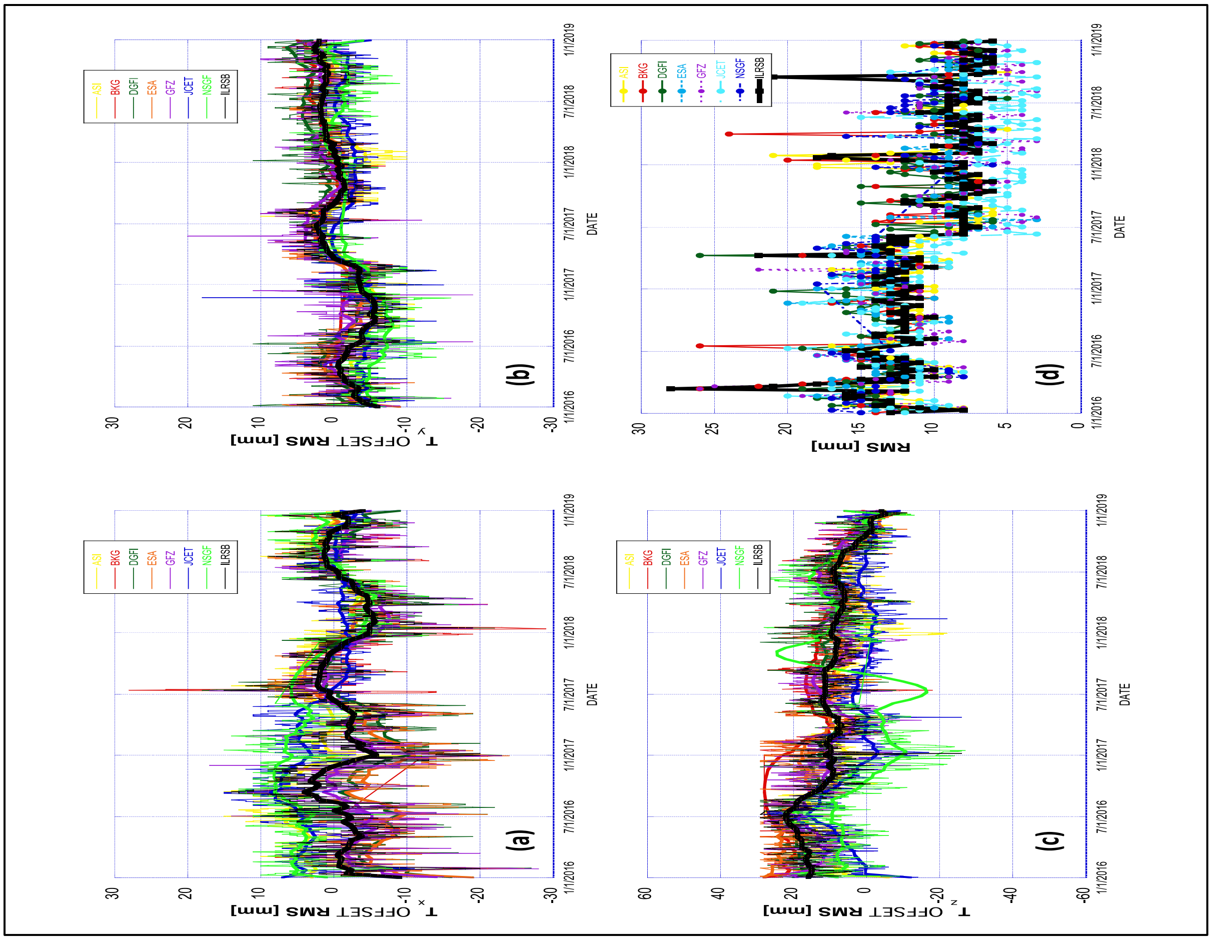

Figure 7-18. Daily TRF origin offsets from that of ITRF2014/SLRF2014 for each AC submission and the JCET CC combination ILRSB (a through c), and the Core Site RMS after the combination (d) over 2016-2019. Note the significant drop in RMS after the adoption of ITRF2014 (07/01/17).

Recent Progress and CC Improvements

The completion of the ITRF2014 model in late 2015 required the subsequent adoption of the new model as the a priori standard for all official ILRS applications. This step was delayed considerably due to the delayed release of the associated EOP series, IERS 14 C04, which for consistency, would have to be used in association with ITRF2014. The ILRS ASC switched to ITRF2014 on July 1, 2017, following the resolution of frequent and undocumented updates of the public version of the IERS C04 series. By that time, we had created an extension of ITRF2014, including a number of SLR sites that were not present in the official release in a similar fashion as it was done with ITRF2008. The resulting expanded model is called SLRF2014 and it is in the ITRF2014 frame by construction.

Related to the IERS EOP series delayed release was also the confusing situation with the IERS Mean Pole (MP) that was to be used by all Services. In 2015 IERS had released a Fortran routine (IERS_CMP_2015.f) that generated the MP position on a requested date. To overcome the unavailability of the extended MP series we generated an extension of the original routine using a linear prediction up to 2021 and delivered the new routine (ILRS_CMP_2016.f) to the ASC for use. Eventually, at the 2017 Unified Analysis Workshop the proper MP definition and modeling was addressed, and an entirely new and simplified model was adopted by the IERS at the end of the year. The old MP terminology was replaced with the “linear mean pole" and linear formula that will be valid for several decades, based on a linear fit to IERS C01. The new model will be used in the development of ITRF2020.

Technical Challenges

The ILRS ASC decision to change the approach of treating systematic errors at the tracking stations in late 2015 resulted in a cycle of repeated reanalyzes of the SLR data for 1993 to present. Initially as a test over a 4-year period (2005-2008) was performed. Based on the results of this PP the ILRS ASC embarked on tests to perfect the new approach. Eventually, it was agreed that a separate bias would be solved for each of the two LAGEOS, but for the Etalons only a combined one due to the poorer and sparser NP data set. The adoption of the new approach caused several reanalysis cycles due to numerous concurrent modifications of the "target signature model" (aka CoM model). Each of these reanalyzes required a subsequent combination of the individual AC series to produce the combined official and back-up product. In order to facilitate a quick and easy comparison of the results, JCET uploaded the individual AC-estimated biases as well as the combined results on an online data base accessed through the JCET Portal from the "Systematic Error Monitoring Project" (*http://geodesy.jcet.umbc.edu/ILRS_AWG_MONITORING/*) option.

The combination results for the two LAGEOS satellites were used to form the weighted mean for each site, over its period of contribution to the combination. This long-term mean bias is not for use in modeling the systematics at the stations but rather to quickly categorize the stations according to how serious or not their systematics are. We arbitrarily set ±10 mm as a boundary of the two predominant groups of stations, with the majority of the strong stations having bias magnitudes of less than 10 mm and the less capable sites significantly larger than 10 mm.

When this graphic categorization was first done with the 2018 combination, it became apparent that the preponderance of biases was positive, with very little difference between the two LAGEOS targets for most systems. This systematic behavior of the biases in a network of very diverse technology, mode of operations, observing crews, etc., could only be explained by a common model error for the majority of the stations: the adopted CoM model that was several years old and based on system information that were by that time fairly old and inaccurate due to the constant system upgrades and changes in the network, which do not usually get recorded in the stations' site log at the same time as they occur. This actually proved to be very true and in 2017 a revision of the model was undertaken by the group of experts led by the NERC AC. This eventually resulted in a new model which was since updated several times, the last one being November of 2019 (*public version*). The differences of the two models are reflected in the change of behavior of the long-term biases of the network, as displayed in Figures 7-19(a) and 3(b).

The next step to complete the SSEM PP is the identification of the change of persistent biases at each site and the computation of the mean value over each period, along with its accuracy estimate. Once this is accomplished the mean biases can be used *a priori* in the re-analysis for the development of ITRF2020. Over the other periods with less systematic bias behavior or stations with completely erratic bias behavior, can be still included in the analysis, however, a weekly bias estimation will be necessary to avoid the introduction of systematics in the product.

Future Plans

The plans for the 2020-2021 period are very much set in stone after our acceptance to participate in the development of ITRF2020. The first year 2020 will be devoted to the finalization of the SSEM bias model and the tests for the introduction of LARES in the final combined product. During 2020 the remaining ancillary models will also be finalized and distributed to the ACs for use in the re-analysis for the ITRF2020. The majority of the ILRS contribution can be completed within 2020, including the combination of the individual AC contributions. It is anticipated that the ASC will switch in 2020 their mode of production to the same standards as those adopted for the re-analysis. This will result in a seamless transition from the reprocessing to the operational products which will at that point be perfectly compatible with the re-analyzed version.

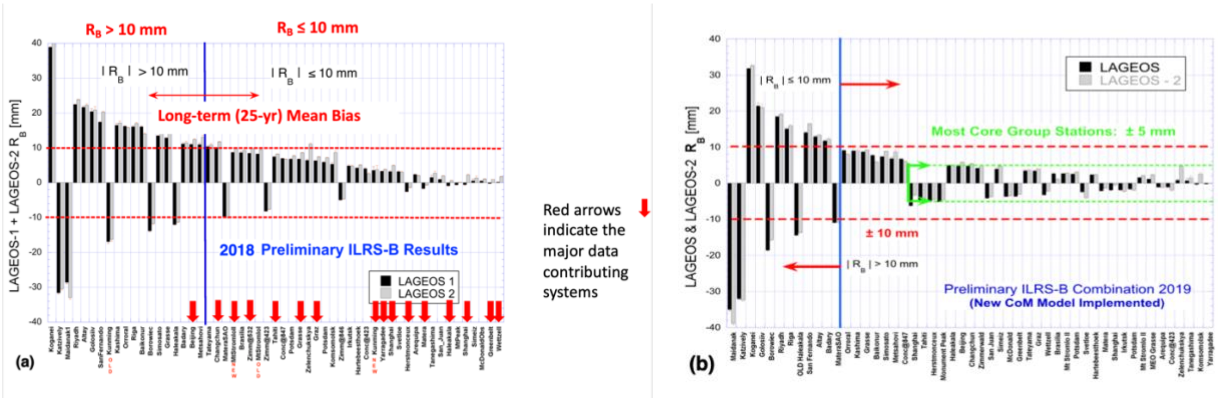

Figure 7-19. Results of the SSEM PP: Long-term bias estimates for the ILRS network (25-yr averages) based on the old CoM model (a) and after the recent adoption of the new CoM model (b). The Core sites now have biases bound by ±5 mm; the increasingly random behavior of these estimates is of note. Overall, large biases are associated with the less capable and low yield systems.

As we approach the end of 2020, the entire 2020 SLR data set will need to be re-analyzed one last time, to benefit from improved ("final") values of the IERS C04 EOP series, and this version will comprise the products to be submitted for generation of ITRF2020. The last couple of months of 2020 should be redone just before the submission to ITRS for the same reason, since IERS C04 is about two months in arears in finalizing its values. Once the entire set of weekly SINEXs is submitted to ITRS, we will work in coordination with the ASI CC (ILRSA) and ITRS to address issues that they will likely encounter with the ILRS submission and ensure the full resolution of each one of them. Upon release of ITRF2020, the ILRS CCs will organize and coordinate the evaluation of the new model, and eventually its implementation within the ILRS.

CC Personnel

Prof. Dr. Erricos C. Pavlis (CC head and ILRS ASC co-chair, member ILRS CB, GB, QCB and MSC), Dr. Magdalena Kuzmicz-Cieslak (CC and ASC member, in charge of daily/weekly data analysis and webmaster), and Mr. Keith Evans (CC and ASC member, in charge of daily/weekly combination of AC solutions and data base management and maintenance).

Figure 7-20. JCET/GSFC CC personnel (left to right): Erricos Pavlis, Magdalena Kuzmicz-Cieslak, and Keith Evans.

Publications

Please refer to the Presentations and Publications under the JCET AC Section.

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ILRS Associate Analysis Centers

Associate Analysis Centers are organizations that produce special products, such as satellite predictions, time bias information, precise orbits for special-purpose satellites, station coordinates and velocities within a certain geographic region, or scientific data products of a mission-specific nature. Table 7-5 lists the current ILRS AACs.

Table 7-5. ILRS Associate Analysis Centers (AACs)

AAC Title and Supporting Agency
Austrian Academy of Sciences, Austria
Center for Orbit Determination in Europe (CODE) Switzerland
Center for Space Research (CSR), University of Texas, Texas, USA
Central Laboratory for Geodesy (CLG), Bulgaria
Delft Institute for Earth Oriented Space Research (DEOS), The Netherlands
Groupe de Recherche en Géodésie Spatiale (GRGS), France
Hitotsubashi University, Japan
Institute of Applied Astronomy, Russian Academy of Sciences, Russia
Institute of Astronomy, Moscow, Russia
Institute for Space Astrophysics and Planetology (IAPS)/National Institute for Astrophysics (INAF) and INFN-Roma2, Italy
Korea Astronomy and Space Science Institute (KASI), South Korea
Main Astronomical Observatory of the National Academy of Sciences of Ukraine (GAOUA), Ukraine
Newcastle University, United Kingdom
Norwegian Mapping Authority (Kartverket), Norway
Pulkovo EOP and Reference Systems Analysis Center (PERSAC), Russia
Russian Metrological Institute of Technical Physics and Radio Engineering (VNIIFTRI), Russia
Russian Mission Control Centre, Russia
Shanghai Astronomical Observatory (SHAO), China
Tsukuba Space Center/JAXA, Japan
Wroclaw University of Environmental and Life Sciences (WUELS), Institute of Geodesy and Geoinformatics (IGG), Poland

CODE (Center for Orbit Determination in Europe), Switzerland

Author: Ulrich Meyer
Responsible Agency: Astronomical Institute, University of Bern

Areas of Interest in the frame of ILRS

The Center for Orbit Determination in Europe (CODE) is a joint venture of the Astronomical Institute of the University of Bern (AIUB), the Swiss Federal Office of Topography (swisstopo), the Federal Agency of Cartography and Geodesy of Germany (BKG) and the Institute of Astronomical and Physical Geodesy of the Technische Universität München (IAPG/TUM). The activities as an Associated Analysis Center of the ILRS are located at AIUB.

CODE acts as an Analysis Center of the International GNSS Service (IGS; Johnston et al, 2017)). Since 2003, a rigorous combined analysis of the GPS and GLONASS microwave measurements is carried out for the final, rapid and ultra-rapid product line of the IGS. From the combined GPS/GLONASS rapid orbits predictions for those satellites tracked by the ILRS are derived and provided to the ILRS.

The IGS is running the MGEX (multi-GNSS extension; Montenbruck et al, 2017) as a pilot project in order to incorporate the new GNSS (like Galileo, BeiDou, QZSS, and NAVIC) and new signals from the established systems into the operational processing. CODE is contributing to this initiative with a five-system solution containing GPS, GLONASS, Galileo, BeiDou, and QZSS for orbits, clocks and related biases (Prange et al, 2016).

CODE provides daily SLR quick-look reports based on all SLR observations to all GNSS satellites carrying retroreflectors from the last six days. Residuals to the SLR observations are computed based on the GNSS microwave–derived orbits and Earth rotation parameters (ERPs) determined at CODE for the IGS. The reports contain the mean, RMS and number of and are distributed daily via e-mail.

Further SLR-based analysis activities

AIUB has also been involved in the orbit determination of a number of Earth observation satellites in low Earth orbits (LEOs) like CHAMP, GRACE, GOCE and Swarm, and has derived static or monthly gravity field solutions that are determined in an extended orbit determination procedure applying the Celestial Mechanics Approach (CMA) developed at AIUB. In recent years the gravity field determination has been extended to the LAGEOS satellites and the SLR-LEOs Starlette, Stella, AJISAI, Larets, LARES and Beacon-C (Sośnica et al, 2015).

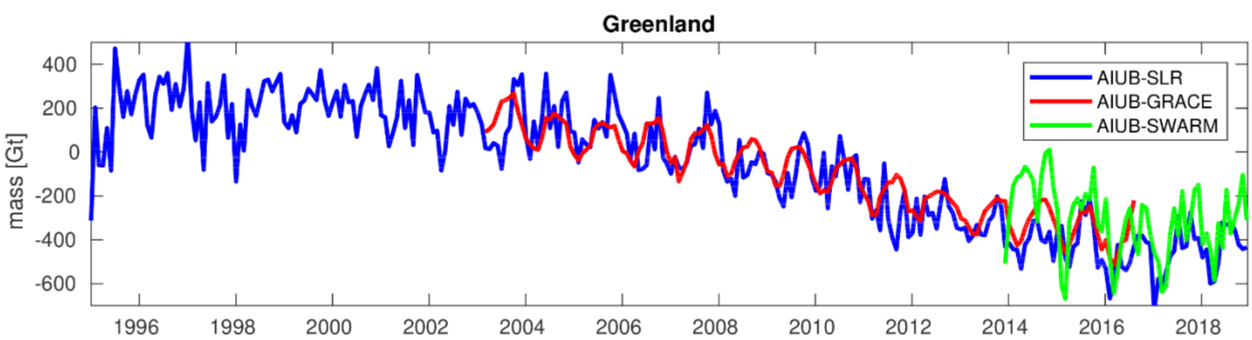

Figure 7-21. Mass change in Greenland derived from monthly SLR, GRACE or Swarm gravity fields (truncated at spherical harmonics degree and order 6).

AIUB had the leading role in the Horizon 2020 project European gravity field service for improved emergency management (EGSIEM; Jäggi et al, 2019). In the frame of this project a prototype scientific combination service for monthly GRACE gravity fields has been developed. Weighted combinations were performed on the solution (Jean et al, 2018) and on the normal equation level (Meyer et al, 2019a) and the latter approach was extended to combinations with SLR-derived gravity field models. The combination service is continued as COST-G, a product center of the International Gravity Field Service (IGFS) under the umbrella of the International Association of Geodesy (IAG).

Recent Progress and Analysis Center Improvements

Lately, SLR and Swarm gravity field combinations on the normal equation level have been studied to derive mass change estimates in areas of major ice melt in Greenland and Antarctica with the goal of bridging the gap between the GRACE and GRACE-FO missions (Meyer et al, 2019b).

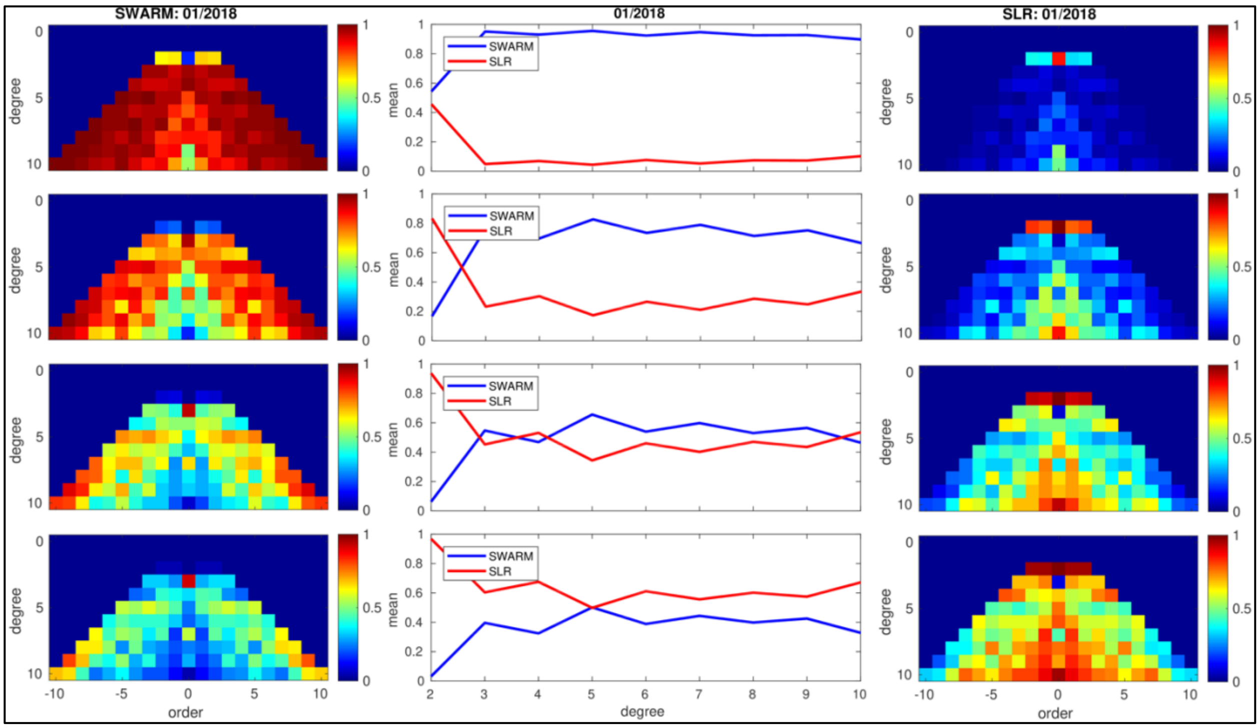

Figure 7-22. Contribution per spherical harmonic coefficient of Swarm (left) or SLR (right) in case of relative weights 100:1 (top), 10:1, 4:1, or 1:1 (bottom) of the Swarm or SLR normal equations in the combination.

In collaboration with BKG it is further planned to extend the COST-G combination service to SLR derived monthly gravity fields of different Analysis Centers (ACs).

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AAC Personnel

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Figure 7-23. Ulrich Meyer

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CSR (Center for Space Research/The University of Texas at Austin), USA

Author: *John C Ries*
Responsible Agency: Center for Space Research

Introduction

In addition to contributing to the SLR data acquisition through its operations at the McDonald Laser Ranging Station (MLRS), the Center for Space Research routinely analyzes the tracking data for several geodetic satellites in support of reference frame evaluation, geodetic conventional model investigations, tests of General Relativity, and monitoring long-wavelength geopotential variations and geocenter motion.

Geocenter Motion

We have been particularly interested in the determination of seasonal geocenter motion with SLR data, since this represents both possible systematic drifts in the terrestrial frame as well as seasonal mass transport within the Earth system at the longest length scale. In this analysis, geocenter motion is defined consistently with the IERS Conventions as the vector from the origin of the ITRF network to the instantaneous center of mass of the entire Earth. In Figure 7-24, we show an estimate of the geocenter motion obtained from SLR tracking to LAGEOS-1/-2 from late 2002 through 2018, using a new approach that attempts to accommodate the higher-degree site loading that affects the SLR estimates of geocenter motion. The network is held fixed to SLRF2014, and the geocenter motion vector is estimated every 60 days.

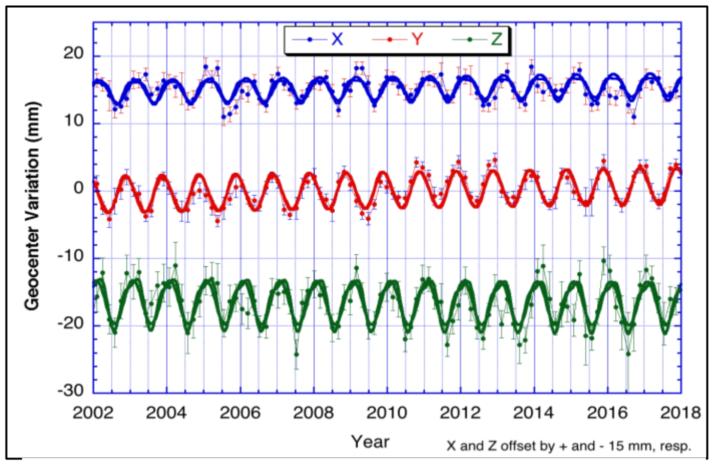

Figure 7-24. Geocenter variations estimated every 60 days from LAGEOS-1/-2. The fit curve is a linear, annual and semi-annual term. A small slope of +0.1 mm/y is observed in Y.

The annual variations determined from the CSR series agree well in both amplitude and phase with other observations from GPS global inversion, a number of geophysical model predictions and combinations of GRACE and ocean bottom pressure models, as seen in Table 7-6 (for more details, see Ries, 2016). The only significant discrepancy is with SCW for the amplitude and phase of the seasonal variation in Z. The SCW technique relies on a global ocean model and GRACE to determine the degree-1 terms. It may be that the ocean model is not fully capturing the seasonal mass variations at high latitudes.

Long-period Variations of the Earth's Gravity Field and the Mean Pole

A few papers published in 2014 and 2015 explained that the IERS conventional model for the mean pole, which at the time was the filtered mean pole (annual and Chandler variations removed), was incorrect for the computation of rotational deformation (aka the pole tide). Instead, the mean pole should be a strictly linear model, which presumably would be driven by GIA. In 2017, we explored the ramifications of changing the mean pole model to a linear model and proposed a linear pole model that was a fit to the entire filtered mean pole time series from 1900 to 2015. One of the effects of this new mean pole model, which dominantly affects C21 and S21, appeared to make the estimates of C21 from LAGEOS-1 and -2 agree better with the prediction from the filtered mean pole (see Figure 7-25). The agreement for S21 was also slightly improved though not as significantly as for C21. This suggests that the rotational deformation model was more correct using the linear mean pole (see Ries and Desai, 2017 for more detail). Based on these results, the linear mean pole model was adopted for computing rotational deformation in the IERS Conventions.

Table 7-6. Estimates of annual amplitude (mm) and phase (deg) from CSR compared to several geodetic and geophysical model estimates. The amplitude and phase are defined by amp*cos(ωt-phase), where t is years past January 1 and ω is the annual frequency. (SCW refers to Swenson, Chambers and Wahr, 2009).

Comparison	X (amp)	X (phase)	Y (amp)	Y (phase)	Z (amp)	Z (phase)	
SLR (L1/L2)	1.9	50	2.8	321	3.9	28	This study (mean of 4 SLR solutions using ITRF2005 and 2014)
GPS loading + GRACE + OBP	1.9	41	2.9	329	3.7	25	Mean of GPS global inversion results
New 'Climatological model'	1.9	45	2.9	325	3.8	26	Average of SLR and GPS results
Geophysical models	2.3	31	2.2	333	3.1	33	Mean of 8 geophysical models
GRACE+Ocean Model	2.2	43	3.0	333	2.7	42	SCW, 2008 (updated 2012, AOD restored)
AOD	1.3	9	1.6	350	0.9	364	AOD1b (RL05, 2002-2014) (GAC)
Climatological model wo AOD	1.3	86	1.5	293	3.3	34	Degree-1 with AOD removed (GSM)
GRACE+Ocean Model	1.3	92	1.4	282	1.8	87	SCW, 2008 (updated 2012, AOD not restored)

As part of our investigation into this issue, it became clear that the drift in C21/S21 is entirely predictable from the filtered mean pole. This suggests that the trend in C21/S21 is not a mass trend signal at all, but rather simply reflects the drift in the Earth's principal axis as it follows the mean rotation axis (the filtered mean pole) (see Wahr, 1987). In other words, the trend in C21/S21 should be ignored when computing mass redistribution from GRACE. As an experiment, the effect of the linear mean pole was also forward-modeled in the analysis. As is apparent in Figure 7-25 (light blue line), the trend in C21 can be entirely explained by the drift in the mean pole. More study is required to verify if this conclusion is correct and should be considered when computing mass trends from GRACE.

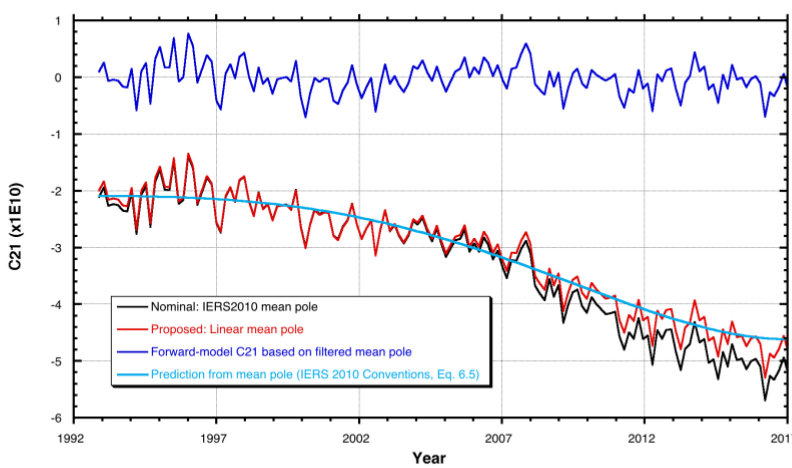

Figure 7-25. Estimates of C21 from LAGEOS-1 and -2, based on various modeling choices.

Analysis of the four-decade time series of C20 from SLR data was found to show a significant variation related to the strong El Niño-Southern Oscillation events with periods of 2-6 years. In particular, the variation related to the powerful 2015-2016 El Niño that peaked during November-December of 2015 was one of the strongest on record (see Cheng and Ries, 2018).

Future Plans

We plan to continue the analysis of the low-degree gravity variations and geocenter from SLR as well as investigate the possible sources of the scale difference between SLR and VLBI. We are particularly interested in the estimation of GM from targets other than LAGEOS-1 and -2.

AAC Personnel

Figure 7-26. Analysis working group members at the University of Texas at Austin (left to right) : John Ries, Minkang Cheng.

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Areas of Interest

We always seek to make full use of the high precision measurement of satellite laser ranging and look into various aspects ranging from satellite dynamics to reflector optical responses. We also routinely provide quality control information to the ILRS stations.

Recent Progress and Analysis Center Improvements

We have developed our analysis package "c5++" since 2010. It is being used not only by Japanese institutes but also by several institutes in Europe.

The rapid quality check reports are being updated every 6 hours on our website: *http://geo.science.hit-u.ac.jp/slr/bias/* (also shown in Figure 7-27)

where a number of new satellites have been added to the analysis in the past few years. The international quality control activities including ours are published largely helped by 9 coauthors worldwide (Otsubo et al., 2018). We also presented a longer-term, more precise assessment at the consecutive three workshops in Potsdam, Riga and Canberra which is available at the ILRS NESC Forum (*http://sgf.rgo.ac.uk/forumNESC/index.php?board=15.0*).

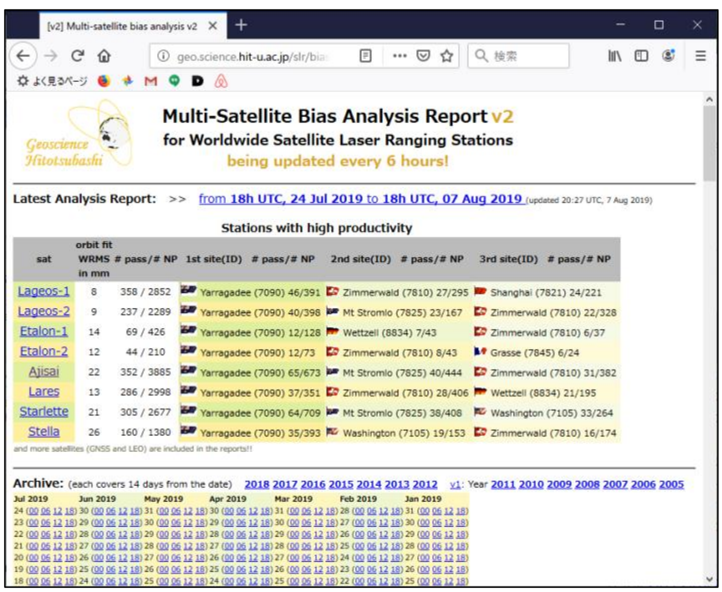

Figure 7-27. Six-hourly quality control reporting service at Hitotsubashi University.

We detected interesting features in the estimates of solar radiation pressure coefficients (C_R) of LAGEOS and Ajisai. LAGEOS-1 C_R is always larger than LAGEOS-2 C_R due to unknown reasons, but the reason why Ajisai's C_R is even smaller with a periodic wobble can be well explained with the optical property of Ajisai (Hattori and Otsubo, 2019).

A simulation study was conducted with Japanese colleagues to find an effective way to expand the SLR tracking network. The best place depends on the geodetic parameters, but in general, our study showed the weakness of the existing ILRS network lies in the high latitude area of the southern hemisphere

(Otsubo et al, 2016). Later, Otsubo served as a PI of a feasible study of Syowa (Antarctica) SLR and an on-site site survey was conducted by the National Institute of Polar Research in 2018.

During a sabbatical year, Otsubo stayed with NERC/BGS Space Geodesy Facility, UK (May-August 2016), GeoForschungsZentrum, Germany (September-December 2016), and Chalmers tekniska högskola, Sweden (January-March 2017).

Otsubo served as a guest professor of National Astronomical Observatory of Japan (2016-2019) and will serve as a guest professor of Institute of Space and Astronautical Science, JAXA (2019-). Our software "c5++" is being applied to a deep space mission Hayabusa-2, in particular its laser altimeter data.

Technical Challenges and Future Plans

Precise force modeling for earth radiation pressure is ongoing, and we plan to test various atmospheric delay models. We would like to learn precise attitude modeling of non-spherical satellites from the DORIS community.

AAC Personnel

Hitotsubashi AAC work has mostly been done by T Otsubo, who is helped by assistant Ms. Mihoko Kobayashi and collaborated with his current and past students.

Figure 7-28. T. Otsubo in front of our quality control computer.

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Areas of Interest

IAA RAS routinely produces lunar and planetary ephemeris EPM. The lunar part of EPM is important for different theoretical and applied studies, including modeling of the lunar interior, building lunar and Earth-lunar reference frames, and planning future lunar missions. The lunar part of EPM relies solely on LLR observations made since late 1969 at different observatories. IAA RAS has received status of an ILRS Lunar AC in 2018. IAA RAS works closely with other analysis centers and LLR observatories, in the joint effort to improve the lunar dynamical model and provide the best lunar reference frame.

Recent Progress and Analysis Center Improvements

Since version EPM2015, the dynamical model of the Moon in EPM is based on DE430 model and includes:

- perturbations of the orbit of the Moon in the gravitational potential of the Earth;
- torque due to the gravitational potential of the Moon;
- perturbations of the orbit of the Moon due to lunar and solar tides on the Earth;
- distortion of the Moon's figure as a result of its rotation and Earth's gravity;
- torque due to the interaction between the lunar crust and the liquid core.

In the lunar part of EPM2017, more recent LLR observations (until the end of 2016) were used. New infrared observations that are now regularly performed at Grasse have dramatically improved the accuracy of the ephemeris. Unfortunately, no LLR observations were provided from Apache Point Observatory since the end of 2016. Historical data from Crimean Astrophysical Observatory (1982–1984) was processed and its accuracy confirmed. Figure 7-29 gives an estimate of the accuracy of the lunar frame in EPM ephemeris.

Coordinate	3σ
A11 X	14.5 cm
A11 Y	19.4 cm
A11 Z	5.3 cm
L1 X	15.7 cm
L1 Y	13.9 cm
L1 Z	8.5 cm
A14 X	12.8 cm
A14 Y	19.9 cm
A14 Z	5.4 cm
A15 X	11.5 cm
A15 Y	18.8 cm
A15 Z	7.9 cm
L2 X	14.0 cm
L2 Y	16.5 cm
L2 Z	7.5 cm

Figure 7-29. Uncertainties of the lunar coordinates of the five retroreflectors basing on LLR observations of 1970–2017.

Three web applications have been developed that provide free ephemeris and LLR-related service to users worldwide. The online ephemeris service (*http://iaaras.ru/en/dept/ephemeris/online/*) provides, among other things, geocentric position and physical libration of the Moon. LLR pointing service (*http://iaaras.ru/en/dept/ephemeris/llr-pointing/*) provides important data for planning LLR observations in an arbitrary observatory. The LLR O-C web service (*http://iaaras.ru/en/dept/ephemeris/llr-oc/*, Figure 7-30) allows to view the residuals (O−C) of past LLR observations and also of observations uploaded by the user.

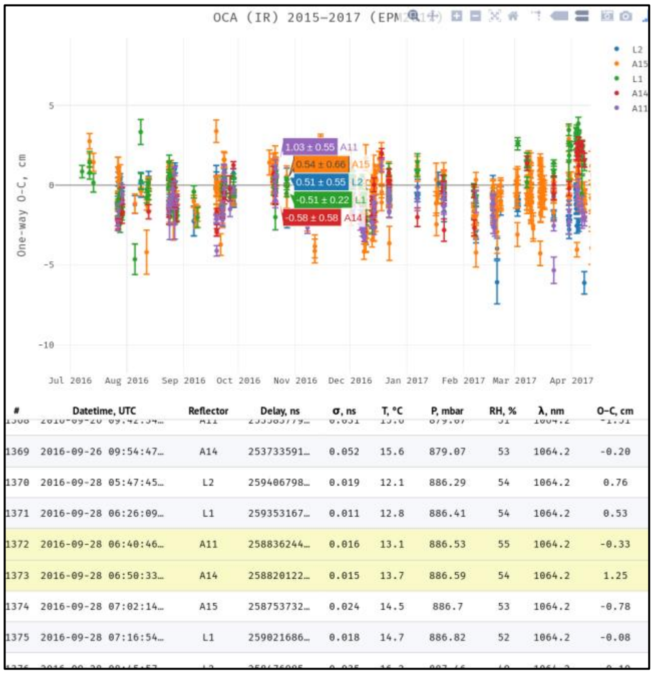

Figure 7-30. LLR O−C webpage made by IAA RAS.

Technical Challenges

A number of developments were undertaken to support the planned new Russian LLR station; however, the construction is being delayed, mainly due to the optical part of the station.

Future Plans

The routine processing of the LLR observations should continue. The next, improved version of EPM, including improved lunar ephemeris, is scheduled for release in 2020.

Research must continue in the areas of:

- Finding the cause of nonzero S21 gravity coefficient in the lunar solution. It is linked to the lunar model, which does not quite represent reality. Mathematically, if the Moon behaved according to the model, the S21 must be zero. There are two possible directions towards the improvement of the model: the first one is the model of the lunar core, and the second one is the model of the tidal response of lunar gravity field.
- Exploration of the possibility of Ephemeris-ICRF tie via LLR.
- Testing general relativity with LLR.

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- Dmitry Pavlov (*dpavlov@iaaras.ru*): responsible for implementation of the lunar part of EPM, and also for the online ephemeris service (*http://iaaras.ru/en/dept/ephemeris/online/*) and the online LLR pointing service (*http://iaaras.ru/en/dept/ephemeris/llr-pointing/*).
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LARASE (LAser RAnged Satellites Experiment), Italy

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Areas of Interest

LARASE is an experiment funded by the Italian National Institute for Nuclear Physics (INFN), National Scientific Commission II (CSN2) on Astroparticle Physics Experiment. We perform measurements of relativistic effects with laser-ranged satellites (LAGEOS, LAGEOS-2, and LARES) in the weak-field and slow-motion limit of Einstein's theory of General Relativity (Lucchesi et al., 2015 and Lucchesi et al., 2017).

Furthermore, we develop new models for the non-conservative forces acting on the cited satellites.

Products:

- State vector of the satellites
- Components of the spin vector of the satellites
- Accelerations on LARES due to the neutral drag with several atmospheric models

Recent Progress and Analysis Center Improvements

Concerning the models, in the last years we developed a new model for the spin evolution of the considered satellites named LASSOS (LArase Satellites Spin mOdel Solutions), based on the solution of the full set of Euler equations (Visco and Luccesi, 2018). The neutral drag perturbation on LARES has been handled in synergy by computing the drag acceleration with SATRAP and performing the POD with GEODYN (Pardini, et al, 2017 and Pardini et al, 2018). Concerning the solid and ocean tides models, we considered their errors (on the basis of IERS Conventions) in relation to the Lense-Thirring effect measurement (Pucacco and Lucchesi, 2018).

Recent improvements concern a model for the Earth gravity field even zonal harmonics based on linear fits to GRACE monthly solutions in relation to the Lense-Thirrimg effect measurement. Finally, we performed a new precise and accurate measurement of the Lense-Thirring effect on the combined orbits of LAGEOS, LAGEOS-2, and LARES (Lucchesi et al., 2019).

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Technical Challenges and Future Plans

We plan to include LARES-2 in our analyses after its launch, and to outline a dedicated dynamical model for the non-conservative forces acting on it. The thermal trust accelerations will be computed for the two LAGEOS and LARES satellites. We also plan to perform new measurements of gravitational effects with the aim to test the predictions of General Relativity with respect to those of other metric theories of gravitation.

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Areas of Interest

As an AAC, JAXA is providing CPF files of Ajisai, LAGEOS-1, and -2 on a daily basis. Also, as an operator of Tanegashima SLR station, we are interested in the accuracy of the CPF files of Ajisai. We always check the number of observation data of Ajisai available from the CDDIS server.

Recent Progress and Analysis Center Improvements

We evaluated the accuracy of Ajisai's CPF files. A summary of the accuracy of the CPF files assessed by using the overlapping method (Figure 7-31). As conclusions (Figure 7-29):

(1) the positioning accuracy of the CPF files is 0.1 to 0.8 [m]. Since the diameter of Ajisai is 2.15 [m], it is enough for tracking Ajisai.

(2) when the number of observation data decreased, the accuracy of CPF files also decreased.

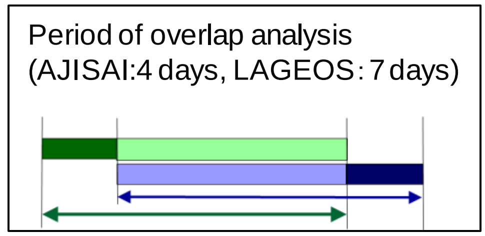

Figure 7-31. Overlap analysis for Ajisai CPF files.

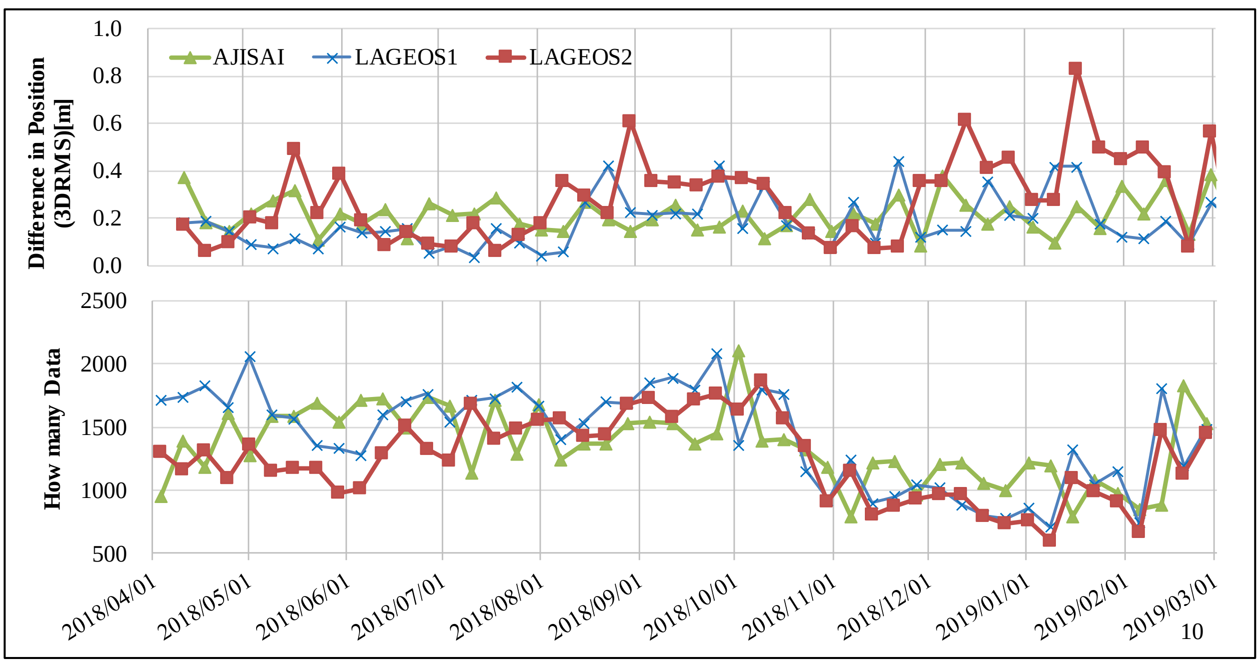

Figure 7-32. Summary of the accuracy of CPF files generated by the JAXA AAC for Ajisai and LAGEOS-1 and -2.

We regard providing CPF files as an obligation for us as the owner agency of Ajisai. We will make an effort to provide its CPF files continuously.

Technical Challenges and Future Plans

In 2020, JAXA will launch a satellite, ALOS-4, in which LRA will be mounted; JAXA will start distributing the CPF files of ALOS-4 as well. Since ALOS-4 will operate in LEO, we have to keep it in our mind to generate accurate CPF files.

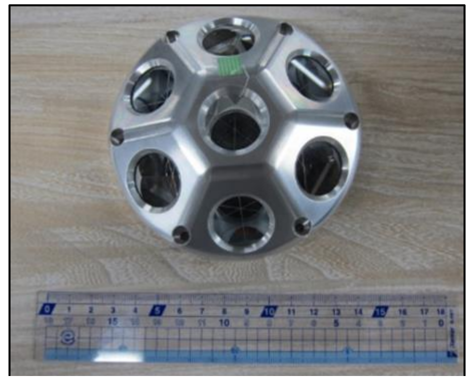

Figure 7-33. Mt. FUJI retroreflector array.

Moreover, JAXA is developing a small, cost-effective, and general-purpose LRA called Mt. FUJI (MulTiple reFlector Unit from Jaxa Investigation). The purpose of this device is not limited to orbit determination. By attaching the Mt. FUJI, all objects change from non-cooperative to cooperative. So, after the operation of spacecraft is over and the object falls into a category of space debris, it becomes easier to track it. We are negotiating with future rocket project teams and satellite missions concerning the usage of Mt. FUJI. Now, we do not have a solution to make accurate CPF files, but we will improve our method by the launch of the first object which mounts Mt. FUJI.

AAC Personnel

Figure 7-24. Staff at JAXA Tsukuba Space Center: left to right) Takushi Sakamoto, Takehiro Matsumoto, Yuki Akiyama, Shinichi Nakamura, and Kazuhiro Yoshikawa.

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Areas of Interest

The ILRS Associated Analysis Center (AAC) at the Institute of Geodesy and Geoinformatics, Wroclaw University Of Environmental and Life Sciences (IGG WUELS) was established in March 2017 providing a service called as multi-GNSS Orbit Validation Visualizer Using SLR (GOVUS) as its main component.

At a time of growing demand for the multi-GNSS constellation, civil and scientific users need intuitive and real-time information about the quality of available multi-GNSS products. Processing of GNSS data for all satellite navigation systems is complicated due to several satellite structural aspects such as various frequencies of transmitted signals or differences in the shape of satellites' bus and solar panels. Satellite Laser Ranging (SLR) technique can be used as an independent validation for the orbit products.

Moreover, the research team, which contribute to the IGG ILRS AAC, focuses on the processing of SLR observations. Three main branches of interest in the research activities are: (1) precise orbit determination of GNSS satellites using SLR observations; (2) troposphere delay modeling for SLR measurements, (3) estimation of global geodetic parameters using SLR observations to geodetic, GNSS, and LEO satellites i.e., Earth rotation parameters (ERPs), geocenter coordinates (GCC), scale of the reference frame, station coordinates and gravity field.

Recent Progress and Analysis Center Improvements

The GOVUS service (Zajdel et al., 2017) is addressed to users of multi-Global Navigation Satellite System (multi-GNSS) orbit products and SLR stations belonging to the ILRS, which track GNSS satellites. The main tasks of the developed service are to (1) store archival and current information about the ILRS laser stations and multi-GNSS satellites; (2) store the multi-GNSS microwave orbit validation results using SLR; (3) allow for fast and advanced online analyses on the stored dataset; (4) provide an autonomous computing center; and (5) generate up-to-date dataset and reports. Among all the current providers of multi-GNSS orbits, only the products delivered by the Center for Orbit Determination in Europe (CODE) are currently being validated as a representative example of 5-system orbit products delivered in the framework of MGEX. CODE multi-GNSS orbit includes particular types of satellites: GPS, GLONASS of type M and K, Galileo of type IOV and FOC, BeiDou-2 of type MEO and IGSO and QZSS.

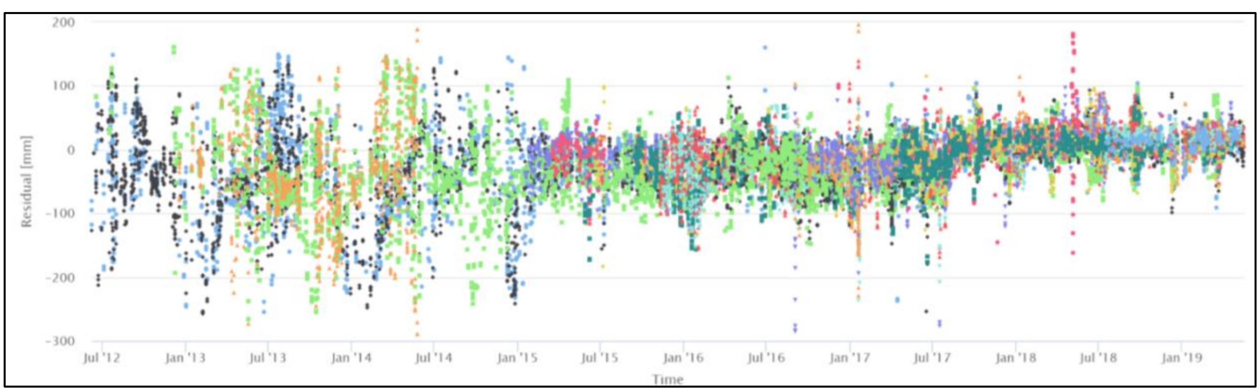

Figure 7-35. Example of the plot from the GOVUS service; Time series of SLR residuals for Galileo satellites in the period 2012-2019.

GOVUS is available at *http://www.govus.pl*. Daily reports of SLR validation are available at *https://www.govus.pl/slr/daily*.

Most of the functions of the GOVUS service were presented at the consecutive ILRS workshops in Riga and Canberra at the Clinic Session. Moreover, the GOVUS service has been presented to the GNSS community at the 6th Galileo Science Colloquium 2017 in Valencia.

The publication effort of the research group at the IGG ILRS AAC for the period 2016-2019 covers 12 articles in the key international journals.

Bury et. al (2019a) summarized the GNSS-intensive tracking campaigns conducted by the International Laser Ranging Service and provides results from multi-GNSS orbit determination using solely SLR observations.

Bury et. al (2019b) described the inconsistency between solutions based on the microwave (GNSS) and optical (SLR) observations which may arise from the omission of the impact of atmospheric pressure loading, especially the nontidal loading (ANTL) part. The systematic shift of the estimated SLR station coordinates, which arises from the ANTL omission, is called the Blue-Sky effect. The offset is related to the long-term averaging of ANTL for SLR observations which are provided in sparse intervals, unlike GNSS, which observes continuously.

Drożdżewski et al. (2018) presented the sensitivity and capability of the SLR observations for the recovery of azimuthal asymmetry of the atmosphere delay above the SLR stations, which can be described as horizontal gradients of the troposphere delay. They concluded that SLR can be employed as a tool for the recovery of the atmospheric parameters with a major sensitivity to the hydrostatic part of the delay. Moreover, the so-called Potsdam Mapping Function (PMF) dedicated to SLR observations has been developed (Drożdżewski et al. 2019) and troposphere effects in global geodetic parameters were tested.

Sośnica et al. (2018a) showed a solution strategy with estimating satellite orbits, SLR station coordinates, geocenter coordinates, and Earth rotation parameters (ERP) using SLR observations to 2 Laser Geodynamics Satellites (LAGEOS) and 55 GNSS satellites. Integration of SLR measurements to GNSS and LAGEOS satellites leads to a substantial increase in the number of weekly solutions and improves the consistency of ERP estimates w.r.t. the GNSS microwave-based results. Sośnica et al. (2019) described also the corresponding results using SLR observations to GNSS satellites only.

Sośnica et al. (2018b) used SLR observations to Galileo satellites for the validation of different orbit empirical models with a special focus put on Galileo satellites in eccentric orbits. The SLR satellite signature effect was analyzed for single-photon and multi-photon. Kaźmierski et al (2018) and Katsigianni et al. (2019) used SLR observations to GLONASS, Galileo, and BeiDou for the validation of the quality of real-time and final orbits provided by the French Space Agency CNES.

Strugarek et al., (2019) used SLR observations to GOCE satellite for the quality assessment of kinematic and reduced-dynamic orbits as well as for the assessment of the impact of the solar and geomagnetic activities on different types of GOCE orbits.

Zajdel et al. (2019) compared the results of the geocenter coordinates delivered in the SLR solution based on LAGEOS satellites and the multi-GNSS solution, which include GPS, GLONASS and Galileo satellites. They concluded that the geocenter offset in the solution with the inhomogeneous distribution of multi-GNSS stations, which is a similar situation to the core SLR network, is generally closer to the SLR time series, which may indicate the network effect in the GCC estimates.

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Technical Challenges and Future Plans

Covering more satellites: LAGEOS, LARES, and selected LEOs: GRACE, GRACE-FO, Swarm, Sentinel-3A/B.

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Lunar Associate Analysis Centers

Lunar Associate Analysis Centers process normal point data from the Lunar Laser Ranging (LLR) stations and generate a variety of scientific products including precise lunar ephemerides, librations, and orientation parameters which provide insights into the composition and internal makeup of the Moon, its interaction with the Earth, tests of General Relativity, and Solar System ties to the International Celestial Reference Frame.

LLR has shown a strong capability to put Einstein's relativity theory to the test and to improve the limits for a number of relativistic parameters. In addition, lunar science and many quantities of the Earth-Moon dynamics could widely be studied. LLR data analysis within the ILRS is carried out by few major analysis centers. Current Lunar Associate Analysis Centers within the ILRS are listed in Table 7-7.

Table 7-7. ILRS Lunar Associate Analysis Centers (LAACs)

LAAC Title and Supporting Agency
Institute of Applied Astronomy, Russian Academy of Sciences (IAA RAS), Russia
Institut für Erdmessung/Forschungseinrichtung Satellitengeodäsie (IFE/FESG), Germany
Istituto Naz. di Fisica Nucleare - Laboratori Naz. di Frascati (INFN-LNF), Italy
Jet Propulsion Laboratory (JPL), Pasadena, California, USA
Paris Observatory Lunar Analysis Center (POLAC), France
University of Texas Analysis Center for LLR, Austin, Texas, USA

IAA RAS (Institute of Applied Astronomy Russian Academy of Sciences), Russia

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Areas of Interest

Lunar activities at the IAA RAS are summarized in their AAC report found previously in this section.

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Areas of Interest

IfE/FESG analyzes LLR data to carry out dedicated research in the following fields: relativity, reference frames, earth rotation, selenophysics.

Recent Progress and Analysis Center Improvements

The modelling of the Earth-Moon dynamics – as a central element of the IfE LLR analysis tool – has been updated in several points.

In the ephemeris computation, the model of the gravitational effects on the Moon was extended. The interaction of the Sun with the lunar gravity field up to degree and order 3 and the interaction of the planets with the lunar gravity field up to degree and order 2 are used to reduce the specific modelling inaccuracy well below the 1 mm threshold. To reach the same ephemeris precision for the Earth-Moon system, the interaction between the point-mass Earth (Moon) with the gravity field up do degree and order 6 for the Moon (Earth, just zonal parts) was included. The figure-figure interaction between Earth and Moon can now be computed up to any degree and order of the gravitational field of both bodies. The effects are added to the equations for translational and rotational motion. The gravitational coupling of the complete degree-2 field of the Earth with the degree-3 field of the Moon has to be considered to get an ephemeris precision below 1 mm.

A further large improvement was the update of the modelled solid Earth tides and the implementation of the consistent rotational model of the Moon as a two-layered body with a solid mantle and fluid core according to the DE430 ephemeris [Folkner et al., 2014]. The tide-induced variations of the selenocentric reflector coordinates are now modelled according to the degree-2 variations in Petit and Luzum (2010) which were adapted to the Moon.

The overall improvement of the IfE-analysis model is reflected in the reduction of the post-fit residuals of about 30 % compared to the previous solution (Figure 7-36). Since 2006 the weighted rms reaches a value of about 1-2 cm. Nevertheless, some un-modelled effects in the longitude libration remain at this stage and have to be investigated in future studies.

The accuracies of the estimated parameters also benefitted from the updated modelling [Biskupek, 2015; Hofmann, 2017]. Hofmann et al. (2018) give the recent results for station and reflector coordinates, nutation coefficients and Earth rotation corrections. The validity of Einstein's theory of gravitation has been studied using various test parameters. Within the achieved accuracy of our LLR analysis, no deviations from Einstein's theory were detected. The most important results include the estimation of improved limits for a possible temporal variation of the gravitational constant with $\dot{G}/G_0 = (7 \pm 8) \times 10^{-14}\,\mathrm{yr}^{-1}$ and a possible violation of the equivalence principle with $\Delta(m_g/m_i)_{EM} = (3 \pm 5) \times 10^{-14}$ [Hofmann/Müller, 2018]. Further studies with more LLR NP in infrared show the benefit of that observations for relativistic investigations. Special analysis of the LLR residuals was performed to study a possible equivalence principle violation due to assumed dark matter in the center of our Galaxy. Here, the amplitude of a possible anomalous range oscillation with a sidereal period was determined. Again, no violation within a realistic error limit of 1 - 2 mm was found [Zhang et al., 2020].

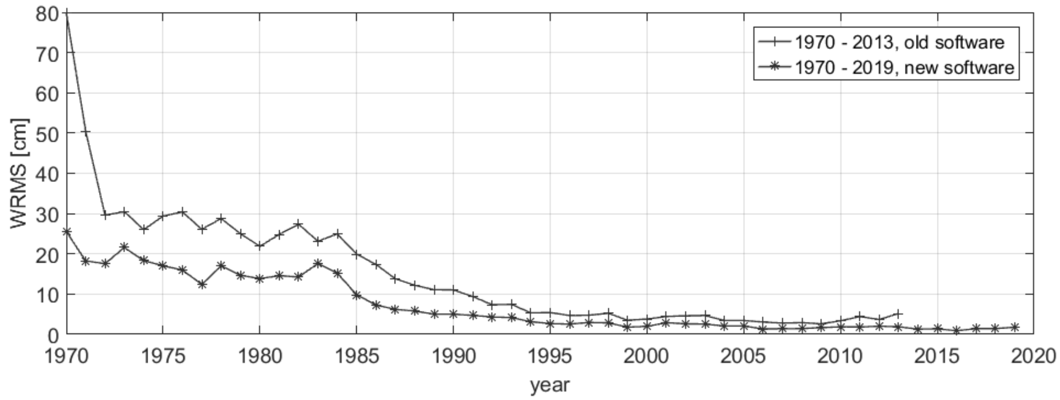

Figure 7-36: Comparison of the annual weighted rms (wrms) of the one-way post-fit residuals: NP between 1970 and 2013 analysed with the old software and NP between 1970 and 2019 analysed with new software.

In a simulation study, Hofmann (2017) investigated the impact of new observatories on the Earth and reflectors on the Moon for the determination of different parameters. Even a single corner cube reflector [Currie et al., 2013] in a position close to the edge of the visible lunar disk at medium selenocentric latitude would well support the modelling of the rotational motion and therefore would improve the results of the LLR analysis.

Technical Challenges and Future Plans

Further plans comprise the improved modelling of the lunar interior, ephemeris calculation and analysis of novel differential LLR data.

LAAC Personnel

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Areas of Interest (Lunar Science Activities in a Nutshell)

Current understanding of our Universe passes through the spinous issue of constraining the most suitable theory of gravity that explains the motion at large scales of universe's expansion history. Einstein's theory is actually passing several tests and commonly one assumes that its validity lies on four different typologies of tests, although more recently new developments have been made in the field of black hole and gravitational wave physics. Among all, the Lunar Laser Ranging technique, hereafter LLR, is one relevant possibility in which through direct measurements of time of flight from the Earth to the Moon and back one can find out possible deviations of Einstein's gravity within the Solar System scale. In so doing, optical passive instrumentations can be adopted and for the sake of completeness, this technique is clearly included within weak field approaches to test gravitational theories. Hence its refinement has reached utmost importance, being particularly relevant to cosmologists, in order to distinguish standard gravity from any possible extensions or modified scenarios of Einstein's theory, e.g., for example f(R) theories, modified teleparallel gravity, Gauss-Bonnet corrections to Einstein-Hilbert's action and so forth.

Unfortunately, and quite unpleasantly, the importance of LLR is jeopardized by underestimated data points so far available by means of Earth stations placed all around the world. The sensibility of such data surveys is often not enough to guarantee direct evidences/predictions that open new insights toward non-negligible corrections to gravity. Consequently, the task of simulating LLR data by means of powerful software based on Monte Carlo techniques has increased its importance and is currently one of the most suitable benchmark for forecasting our expectations together with more modern treatments based on statistical learning codes.

Among all, the Planetary Ephemeris Program, hereafter PEP, represents a free available code that aims at understanding the physics of gravitation using LLR data points and simulating either more data or alternative configurations by means of internal Monte Carlo procedures commonly based on Metropolis-Hastings algorithm. The architecture of the code has been firstly developed at Harvard-Smithsonian Center for Astrophysics at Harvard, USA, and aims at generating ephemerides of planets and, above all, of the Moon and particularly it acts as a direct comparison between data and expectations. In fact, the code is thought to simulate LLR and satellite laser ranging data in order to test extended models of gravity, and/or standard gravity, directly with numerical outcomes. In this respect the code verifies possible deviations from Einstein's theory of gravity by taking general relativity and expanding it at low energy domains, obtaining the Post Parameterized Newtonian parameters, hereafter PPN parameters, and confronting them with Monte Carlo simulations previously implemented via heavy Markov chains computed within the code itself.

The comparison has the advantage of being predictive as one assumes the geometry and the placing of laser retroreflectors, i.e., the principal passive instrumentations used for the LLR technique, on the Moon changing the principal properties of these passive optical objects and analyzing how this fact can lead to observable results over PPN parameters. The corresponding bounds are also compared with an evolving Newtonian gravitational constant, G. This perspective may be true since possible variations of G with respect to cosmic time are allowed as effective gravitational constants are assumed as byproduct of the coupling between extra terms coming from new theories of gravitation and the previous version of G, i.e., the one developed by Newton.

Indeed, the idea of checking whether G varies with respect to time turns out to be a direct consequence of assuming an extended theory of gravity in which geometrical additional terms naturally couple with the strength of gravity.

Thus, this prerogative is inferred from the code as consequence of the numerical simulations provided during computations and so far viable constraints have been bounded up to a part over 10^{-16} showing up no relevant differences, at least in the framework of weak field, with standard gravity.

Since currently several evidences, such as dark matter and inflationary epochs, seem to indicate that extended theories of gravity may be used as alternatives to explain the unknown constituents of the universe, it appears clear that future efforts based on LLR will complement the cosmological probes. Further new developments using LLR techniques can be made in order to focus and to refine the sensibility prompted in PEP and in simulations got from analogous theoretical and experimental treatments. The idea is to check any possible deviations from our standard knowledge about gravity and, above all, to understand if, combining more than one data survey can actually be considered as a relevant indication for a more appropriate comprehension of gravity. For example, looking at the dark side of the Moon, in future missions, it would be possible to match cosmological data with the ones provided in PEP and with simulations that will employ other data sources. The idea is to provide contour plots, based on 68% and 95% confidence levels, of PPN parameters that are intertwined with hierarchical data set analyses in order to fix tighter and stringent limits over the whole picture of our universe.

Recent Progress, Analysis Center Improvements, and Technical Challenges for the Future (Establishment and Activities of the Joint Lab between ASI-CGS and INFN-LNF)

INFN-LNF (Istituto Nazionale di Fisica Nucleare - Laboratori Nazionali di Frascati), in the framework of the activities of its Joint Lab with ASI-Matera (Agenzia Spaziale Italiana - Centro di Geodesia Spaziale 'Giuseppe Colombo', aka ASI-CGS) [1], delivered to ASI, ESA, and NASA-JPL several miniaturized laser retroreflector payloads designed for the Moon, Mars, and other planetary missions. Moreover, INFN-LNF's flagship experiment, MoonLIGHT (Moon Laser Instrumentation for General relativity High accuracy test), the single, solid, large lunar laser retroreflector, was selected by ESA for flight on board on one of the first upcoming Missions of Opportunity in 2021-22; for a very brief introduction to the science of MoonLIGHT, see previous Section, or the following.

Specifically, the *microreflector* payloads designed for the Moon, Mars, and other planetary missions, are, amongst the other, INRRI[4], LaRRI[5], and LaRA[6] (see Figures 7-37, 7-38, and 7-39). [2, 3, 4]:

- Family of laser microreflectors for planetary geology measurements, object of strategic missions of NASA (InSight 2018, Mars 2020) and ESA (ExoMars).
- Two such payloads were launched in 2016: INRRI (Figure 7-37) and LaRRI (Figures 7-37 and 7-40), respectively with the ESA ExoMars 2016 mission, and in 2018 with the NASA InSight 2018 mission; two more will be launched in 2020: INRRI (Figures 7-38 and 7-41), and LaRA (Figure 7-39), respectively with the ESA ExoMars 2020 mission, and with the NASA Mars 2020 mission.

These instruments are positioned by measuring the time-of-flight of short laser pulses, the so-called *laser ranging* technique (for details on satellite/lunar laser ranging and altimetry see the ILRS website *https://ilrs.gsfc.nasa.gov*), which is notionally pictured in Figure 7-42. The goals of the microreflectors and their role as the passive, maintenance-free, long-lived instrument component of a future MGN (Mars

[4] INstrument for landing-Roving laser Retroreflector Investigations.
[5] Laser RetroReflector for InSight.
[6] Laser Retroreflector Array.

Geophysical Network) were solidly proofed thanks to the success of InSight, which will always be the first, *core node* of such an MGN [5, 6, 7, 8].

Figure 7-37. Left: microreflector payload for ESA ExoMars 2016. Right: microreflector payload for NASA InSight 2018.

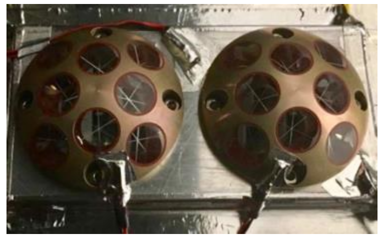

Figure 7-38. Left: microreflector payload for ESA ExoMars 2020. Right: identical spare available at INFN for other international mission opportunities.

Figure 7-39. Microreflector payloads for NASA Mars 2020.

Moreover, science applications of microreflectors include surface geodesy, geophysics (when combined with seismometers, heat flow probes, etc., like the instrument suites of InSight [2] and Apollo[7] [9, 10]) and the test of fundamental relativistic gravity. We performed test physics simulations of the contribution of a 5-microreflector MGN to test General Relativity with the Planetary Ephemeris Program developed by I. Shapiro et al (see for example [11]). Under specific and conservative assumptions (about laser observations from orbit, tracking of the orbiter, etc.) the contribution of this MGN is found to improve the measurements of Gdot/G (possible time changes of the gravitational constant) and of ▯▯ the Parametrized Post Newtonian constant related to gravitational self-energy and to possible violations of the strong equivalence principle. This test will be complementary to (and with experimental errors independent of) the one performed with large-size lunar laser retroreflectors (Apollo 11, 14, 15; Lunokhod 1, 2) observed by lunar laser ranging from Earth since 1969 [12, 13].

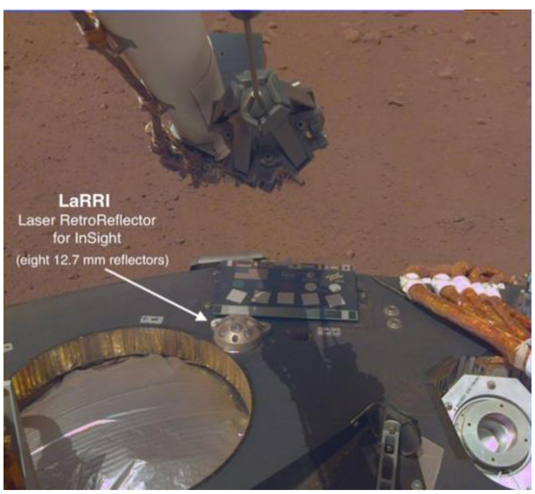

Figure 7-40. LaRRI, on Mars, on the top deck of the InSight lander, in front of the camera calibration targets.

Figure 7-41. INRRI for ExoMars 2020 already installed on the top deck of the landing platform.

Since its very establishment, the main goal of the INFN-LNF's SCF_Lab has been the deployment on the Moon of MoonLIGHT (Figure 7-43): a retroreflector for lunar laser ranging measurements, which will fly in the years 2021-2022. This 100 mm single, solid, large reflector is intended for direct lunar laser ranging

[7] EASEP and ALSEP = Early Apollo Scientific Experiment Package/Payload (Apollo 11) and Apollo Lunar Surface Experiments Package (≥ Apollo 12).

from stations in USA, Italy (ASI-CGS) and France (Grasse). Its main applications are the LGN (Lunar Geophysical Network), and precision tests of General Relativity and new theories of fundamental relativistic gravity. MoonLIGHT was selected by ESA for flight on board one of the first upcoming Missions of Opportunity in 2021-22 (Figure 7-44).

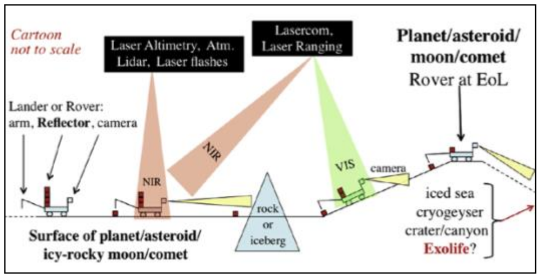

Figure 7-42. Notional concept of microreflectors for solar system exploration research.

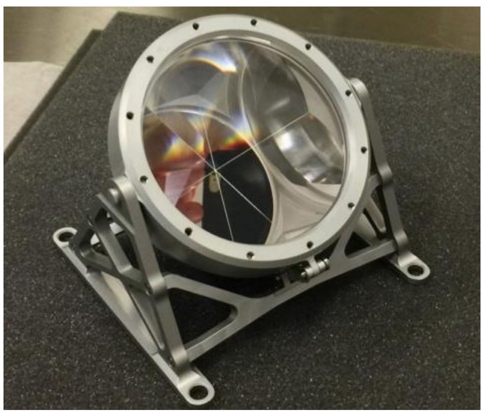

Figure 7-43. MoonLIGHT, retroreflector for lunar laser ranging measurements.

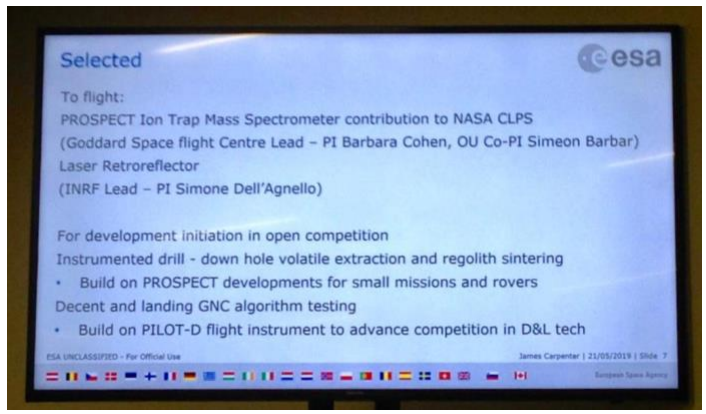

Figure 7-44. Public announcement of MoonLIGHT selection for flight on an ESA Mission of Opportunity at the European Lunar Symposium 2019 by James Carpenter (ESA).

Concerning the experimental importance of MoonLIGHT, one reminds that Einstein's theory of General Relativity (GR) provides a comprehensive description of space, time, gravity and matter at the macroscopic level. Classical tests of GR (e.g., perihelion precession of Mercury, deflection of light, and gravitational redshift) confirmed that the theory is well founded. But they are valid essentially in a weak field. In the last thirty years, several shortcomings of Einstein's theory were found, and scientists began wondering whether GR is the only fundamental theory capable of successfully explaining the gravitational interaction, at all scales. This new point of view comes mainly from the study of cosmology, and of quantum field theory. Therefore, various alternative gravitational theories were proposed which attempt to formulate at least a semiclassical scheme in which GR can be replicated [14]. There are many possible experiments for testing GR and its extensions but most of them are complex (i.e., involvement of atomic clocks, interferometers, etc.). Thus, it is very important to work with the best possible theoretical framework to compare models with observations. An example is the Parametrized Post Newtonian (PPN) formalism [15]. Solar System experiments, like lunar laser ranging, allow us to measure some of these PPN parameters, and thereby to determine which theory of gravity best describes the observed physical phenomena (GR, scalar tensor theories, f(R), or something else).

Future Plans (The European Lunar Symposium 2020 (…and 2021!))

The European Lunar Symposium (ELS), a meeting that soon became annual, is held every year, since 2012, in a different city in Europe. ELS is a meeting and interaction point for scientists and engineers, academics and industry, from Europe and all over the world. Lunar exploration is undergoing a new global surge, and many are the current interests in the exploration of the Moon: astronomical, astrophysical, geological, commercial, resource utilization, and strategic considerations, to its use as an outpost for future human exploration of the Solar System. ELS brings together the European scientific and technical communities interested in various aspects of lunar exploration. In addition, lunar experts from countries engaged in launching lunar missions are also invited to attend this meeting.

Figure 7-45. The original logo of the 'in-person' ELS 2020 (https://els2020.arc.nasa.gov/).

Figure 7-46. The present logo of the 'virtual' ELS 2020 (https://els2020.arc.nasa.gov/).

INFN, for the second time (on eight editions overall - there was no 2013 symposium), is leading the SOC/LOC of the event. As a reference, together with the 2020 website (*https://els2020.arc.nasa.gov/*), one reports also the 2015 website (*https://els2015.arc.nasa.gov/*). The first definition meeting for the event was held in May 2018, during that year symposium.

As of 2nd March 2020, following the disruptions generated by the worldwide outbreak of COVID-19, the Padua 2020 'in-person' ELS went 'virtual'. The perspective attendees were duly communicated by e-mail the change in content fruition for this year ELS. Main (*https://els2020.arc.nasa.gov/*) and local (*https://agenda.infn.it/event/21149/*) websites of the event were correspondently updated to reflect the new state of things. As a consequence, the LOC was suppressed. Despite the unforeseeable and unprecedented calamity, and thanks to the collaboration of the participants, the SOC was able to assemble a 'remarkable' program (available for downloads, together with the collection of the abstracts, from the event websites). As of today (16th April 2020), one counts 198 participants, 80 talks, 40 posters. Finally, as per the 'breaking news' dated 9th April 2020, the board of the conference decided to reassign to INFN the leadership of the 2021 symposium. INFN, for the third time out of nine editions in 2021, will be in charge of the event organization.

LAAC Personnel

The two following lists (one for Scientific Profile, the other one for Technological Profile) are in alphabetic order - they report only the SCF_Lab Team members involved in lunar activities:

- Scientific Profile:
  1. Bellettini Giovanni (Associate) - Full Professor
  2. Casini Stefano (Employee) - Fellowship Holder
  3. Di Paolo Emilio Maurizio (Employee) - Staff Researcher
  4. Filomena Luciana (Employee) - Postdoc
  5. Ioppi Luca (Employee) - Fellowship Holder
  6. Luongo Orlando (Employee) - Staff Researcher

7. Maiello Mauro (Associate) - High School Teacher
8. March Riccardo (Associate) - Senior Researcher
9. Mauro Lorenza (Associate) - PhD Student
10. Muccino Marco (Employee) - Staff Technologist
11. Rubino Laura (Associate) - PhD Student
12. Vittori Roberto (Associate) - Executive Researcher

- Technological Profile:

13. Bianco Giuseppe (Associate) - Executive Technologist
14. Dell'Agnello Simone (Employee) - Executive Technologist
15. Delle Monache Giovanni Ottavio (Employee) - Staff Technologist
16. Porcelli Luca (Employee) - Staff Technologist

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JPL (Jet Propulsion Laboratory), USA

Author: *James G. Williams*
Responsible Agency: Jet Propulsion Laboratory, California Institute of Technology

Areas of Interest

We fit lunar laser ranges from 1970 to the present. The fits determine the lunar orbit including tidal acceleration, orientation of the Moon in space, geocentric station positions and motions, orientation of the Earth in space, Moon-centered retroreflector positions, lunar tidal displacement Love number h_2, tidal dissipation associated with potential Love number k_2 at several periods, dissipation at the lunar fluid-core solid-mantle boundary, and *GM*(Earth+Moon).

The tidal acceleration of the Moon is mainly caused by dissipation due to ocean tides, but tidally induced eccentricity rate has a significant additional contribution from tidal dissipation within the Moon. The orientation of the Earth in space includes precession, obliquity rate, and nutations. The orientation of the lunar body in space over time, the physical librations, and also tidal displacements provide geophysical information on the lunar interior. Tidal dissipation in the Moon is strong in the lowest mantle above the core. The physical librations also give information on dissipation at and flattening of the lunar core-mantle boundary (CMB). One lunar free libration mode is similar to the terrestrial Chandler wobble, but with a 75-year period, while another is a 2.9-year oscillation in longitude. Free libration amplitudes should damp out with time so the two observed sizable lunar free librations require a geologically recent stimulus. The lunar orbit provides a very good test of the equivalence principle, an assumption of general relativity. The orbit is also sensitive to relativity-caused geodetic precession.

Renewed interest in missions to the Moon provides an opportunity to place new retroreflectors on the Moon.

Post-fit and rms residuals are provided to the lunar ranging stations at Observatoire de la Côte d'Azur, France; Apache Point Observatory, New Mexico; Matera, Italy; and Wettzell, Germany.

Publications:

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Müller, J., T. W. Murphy, Jr., U. Schreiber, P. J. Shelus, J.-M. Torre, J. G. Williams, D. H. Boggs, S. Bouquillon, A. Bourgoin, and F. Hofmann (2019), Lunar laser ranging – a tool for general relativity, lunar geophysics and earth science, J. Geod. 93 (issue 11), 2195–2210, doi:10.1007/s00190-019-01296-0

Recent Progress and Analysis Center Improvements

Over the years 2016–2019 we have improved the modeling of lunar ranges. Dynamical model improvements include updating the orientation of the Earth for figure perturbations, relativistic geodetic precession affecting lunar physical librations, and solar radiation pressure on the lunar orbit. In the range model we added separate biases for ranges at 1064 ns and 532 ns, refraction delay in the corner cubes, monthly thermal expansion of reflector arrays, atmospheric pressure loading at stations, and seasonal terrestrial center-of-mass vs. center-of-figure effects. All have very small effects on the rms residuals. Thermal expansion and solar radiation pressure are few millimeter systematic effects for tests of the equivalence principle.

Tidal dissipation causes the Moon to recede from the Earth by 38.2 mm/yr, corresponding to an acceleration in orbital longitude of –25.9 "/cent^2. Tide-caused eccentricity rate affects perigee and apogee by –6 and +6 mm/yr, respectively, so that the perigee recedes by 30 mm/yr and the apogee recedes by 46 mm/yr.

The tidal *Q* of the Moon is around 40–45 at 1 month and 1-year periods, but larger at 3 and 6 years. The strong tidal dissipation is thought to come from a zone of partial melting in the deepest part of the mantle.

The Moon centered positions of the 5 retroreflecting arrays are known to better than 1 m. The arrays have been photographed by the Lunar Reconnaissance Orbiter and their positions are useful for global cartography.

We support an effort to place Next Generation Lunar Retroreflectors on the Moon. The University of Maryland NGLRs would be single solid corner cubes that are 10 cm in diameter. Single corner cubes do not spread the photon arrival times of the return pulse.

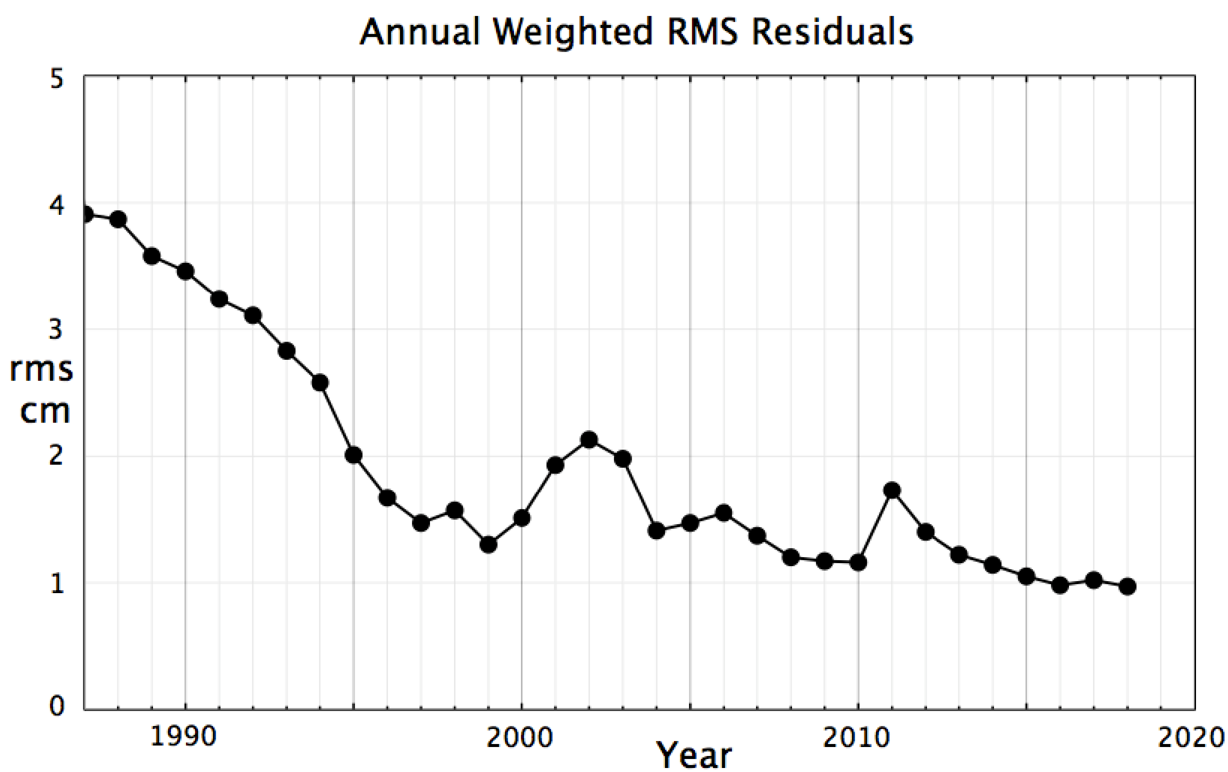

Figure 7-47. Annual weighted RMS residual over the last 3 decades.

The weighted rms residual over the 2016–2019 span is 0.065 ns or 1.0 cm. The four smaller reflectors are fit somewhat better than the larger Apollo 15 array. The figure shows the four-fold improvement in the annual weighted RMS residual over the last 3 decades. Over the recent 4 years there are 4819 ranges to

5 lunar retroreflectors at the Apollo 11, 14, 15 and Lunokhod 1 and 2 sites. The number of observations to the smaller reflectors increased in 2017, 2018, and 2019, which benefits the lunar science results.

Technical Challenges and Future Plans

We will be providing a new numerically integrated lunar ephemeris with physical librations for public use. This will be available to space missions and to the tracking stations for their predictions.

We will examine the model looking for improvements. We will attempt to find the cause of an unexplained contribution to eccentricity rate. We will also study the slightly different alignments of the principal axes of the moment of inertia matrices of the mantle and whole Moon.

A new trigonometric analysis of the numerically integrated physical librations is planned.

We will aid the effort to place Next Generation Lunar Retroreflectors on the Moon. These single corner cubes would be larger than the individual corner cubes used in the Apollo and Lunokhod arrays.

LAAC Personnel

- James G. Williams (*James.G.Williams@jpl.caltech.edu*) does model formulation, development of theory, and data analysis.
- Dale H. Boggs (*Dale.H.Boggs@jpl.caltech.edu*) performs software development and data analysis.
- J. Todd Ratcliff performs Earth rotation analysis, combining LLR results with other techniques.
- Slava G. Turyshev participates in tests of gravitational physics.

Figure 7-48. JPL Lunar Analysis Center staff, left to right: James Williams, Slava Turyshev, Dale Boggs, and Todd Ratcliff.

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Acknowledgment

The research was carried out at the Jet Propulsion Laboratory, California Institute of Technology, under a contract with the National Aeronautics and Space Administration. U.S. Government sponsorship acknowledged.

POLAC (Paris Observatory Lunar Analysis Center), France

Author: *Sébastien Bouquillon, Adrien Bourgoin[8] et Gérard Francou*
Responsible Agency: Observatoire de Paris (SyRTE), Paris, France

Areas of Interest

POLAC (Paris Observatory Lunar Analysis Center) is an ILRS Lunar analysis center founded by J. Chapront, M. Chapront−Touzé and G. Francou in 1996. The original purpose of POLAC was the analysis of the lunar laser ranging observations (LLR) based on the adjustment of their semi-analytical solution of the lunar motion named ELP (Ephémérides lunaires Parisienne) to LLR data. These LLR analyses have allowed us to improve the determination of fundamental astronomical parameters, such as the free modes of lunar physical librations, the tidal secular acceleration of the lunar longitude, or the transformation between celestial reference systems. Since 2010, POLAC also provides the accurate predictions required to achieve Lunar laser ranging observations. From the very beginning, POLAC has always worked in close collaboration with the team of the laser ranging station of Grasse (MéO).

Recent Progress and Analysis Center Improvements

Between 2016 and 2018, the two main activities of POLAC – LLR predictions and LLR analysis – have significantly evolved.

Firstly, concerning the LLR predictions, with the ending of lunar observations at MLRS (McDonald Observatory) at the beginning of 2016, Randall Ricklefs, in charge of calculating LLR predictions for the "International Laser Ranging Service" (ILRS), decided to end this responsibility and it is now POLAC who takes on this task for the LLR community. This increases the international service loads of POLAC which already produced LLR predictions for a small group of stations involved in LLR via a dedicated web interface (*http://polac.obspm.fr/PaV/index.html*). Each day, POLAC now produces LLR predictions for all the five retro-reflectors on Moon under CPF formats (version 1 and version 2) and distributes them to the CDDIS and EDC database systems allowing their use by all the ILRS members and their storage for normal point post-analysis.

Secondly, in an experimental mode, POLAC provides predictions for allowing MeO Grasse station to achieve two-way laser ranging with the retro-reflectors array on board of the lunar satellite LRO (Lunar Reconnaissance Orbiter). The LRO ephemeris we use to compute laser ranging predictions are the ones produced by the LRO navigation team for the observation day in the SPICE SPK format. With this, POLAC computes a Grasse-specific light-time and azimuth/elevation prediction file in the Topocentric Prediction Format (TPF), accounting for the latest Earth Orientation Parameters provided by the International Earth Rotation and Reference Systems Service (IERS). With the help of one of these TPF files, MeO station has succeeded for the first time ever a 2-way ranging with LRO on September 4, 2018. Later two other successful passes have definitively validated the correctness of POLAC LRO-LR predictions.

Thirdly, concerning the LLR analysis, POLAC has upgraded its Lunar solution by substituting to ELP a new lunar ephemeris called ELPN (Ephéméride lunaire Parisienne Numérique). This new ephemeris has been developed by Adrien Bourgoin in the framework of his thesis (Bourgoin, 2016) by numerical integration of the differential equations governing the orbital and rotational motion of bodies in the Solar System and the difference between the Terrestrial Time (TT) and the Barycentric Dynamical Time (TDB) to make the ephemeris self-consistent. Special attention has been paid to the computation of partial derivatives integrated numerically from the variational equations.

8 Post-doctoral student in *Dipartimento di Ingegneria Industriale, Università di Bologna, Forlì, Italy*

One of the achievements of ELPN has been to allow POLAC to take part to the long legacy of testing fundamental Physics with lunar laser ranging. Indeed, even if ELPN was built originally in the General Relativity (GR) framework, it allows for GR alternative theories of gravity as well. One of particular interest is the Standard Model Extension (SME) which parametrizes Lorentz symmetry violations, notably in the pure gravity sector (Bailey et al, 2006) and in the matter sector (Kostelecký et al, 2011) of the formalism. By fitting ELPN in the SME framework to the 50 years of collected data, we have been able to provide stringent and realistic estimates on possible Lorentz symmetry violations arising at the level of the weak and the strong Einstein equivalence principles. These results have been published in two articles in Physical Review Letters (Bourgoin et al., 2016 and Bourgoin et al., 2017). We give in Table 7-8 below the determination of six combinations of SME parameters for which the current best constrain has been achieved by this last study.

Table 7-8. SME Parameters

	SME[9]	Constraints
$\bar{s}^1$	$\bar{s}^{XY}$	$(-0.5 \pm 3.6) \times 10^{-12}$
$\bar{s}^2$	$\bar{s}^{XZ}$	$(+2.1 \pm 3.0) \times 10^{-12}$
$\bar{s}^3$	$\bar{s}^{XX} - \bar{s}^{YY}$	$(+0.2 \pm 1.1) \times 10^{-11}$
$\bar{s}^4$	$0.35\,\bar{s}^{XX} + 0.35\,\bar{s}^{YY} - 0.70\,\bar{s}^{ZZ} - 0.94\,\bar{s}^{YZ}$	$(+3.0 \pm 3.1) \times 10^{-12}$
$\bar{s}^5$	$-0.62\,\bar{s}^{TX} + 0.78\,\alpha(\bar{a}_{\mathrm{eff}}^{e+p})^X + 0.79\,\alpha(\bar{a}_{\mathrm{eff}}^{n})^X$	$(-1.4 \pm 1.7) \times 10^{-8}$
$\bar{s}^6$	$0.93\,\bar{s}^{TY} + 0.34\,\bar{s}^{TZ} - 0.10\,\alpha(\bar{a}_{\mathrm{eff}}^{e+p})^Y - 0.10\,\alpha(\bar{a}_{\mathrm{eff}}^{n})^Y$ $- 0.044\,\alpha(\bar{a}_{\mathrm{eff}}^{e+p})^Z - 0.044\,\alpha(\bar{a}_{\mathrm{eff}}^{n})^Z$	$(-6.6 \pm 9.4) \times 10^{-9}$

References

Bailey, Q. G., Kostelecký, V.A., 2006., “Signals for Lorentz violation in post-Newtonian gravity”, Physical Review D 74, 045001.

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Bourgoin, A., Le Poncin-Lafitte, C., Hees, A., Bouquillon, S., Francou, G., Angonin, M.-C., 2017, “Lorentz Symmetry Violations from Matter-Gravity Couplings with Lunar Laser Ranging”, Physical Review Letters 119, 201102.

Kostelecký, V. A., Tasson, J. D., 2011. “Matter-gravity couplings and Lorentz violation”, Physical Review D 83, 016013.

LAAC Personnel

- S. Bouquillon (coordinator)
- A. Bourgoin, A. Hees & C. Le Poncin-Lafitte (LLR analysis and tests of fundamental physics)
- G. Francou (LLR analysis and data collection)
- T. Carlucci (LLR and LRO-LR predictions)

9 Red parameters ($\bar{s}^{XY}$, $\bar{s}^{XZ}$, etc.) are from the pure gravity sector of the SME (Bailey et al, 2006) while the green parameters ($\alpha(\bar{a}_{\mathrm{eff}}^{n})^X$, $\alpha(\bar{a}_{\mathrm{eff}}^{n})^Y$, etc.) are from the pure matter sector (Kostelecký et al, 2011).

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Section 8:

ILRS Network

Section 8: ILRS Network

Authors: *ILRS Station Contacts*
Editors: *Carey Noll, Michael Pearlman*
Responsible Agency: ILRS Central Bureau

Overview

The ILRS coordinates activities for an international network of Satellite Laser Ranging (SLR) and Lunar Laser Ranging (LLR) stations. The network represents a global consortium of stations that range to ILRS-approved targets for science and engineering applications. The stations are required to follow established ILRS policies and procedures, including maintenance of system site logs and adherence to tracking priorities and restrictions. To facilitate operations and communications, the network is divided into sub-networks by generalized geographic region:

- European Laser (EUROLAS) network
- National Aeronautics and Space Administration (NASA) network
- Western Pacific Laser Tracking Network (WPLTN)

LLR is currently performed at stations in Grasse/France, Matera/Italy, Wettzell/Germany, and Apache Point NM/USA.

Although the general configuration of the ranging stations is similar, they have been developed by different institutions over time, and represent different approaches in technology, operation, and maintenance. ILRS network systems range from legacy technology long proven through many years of operation to newer technologies with enhanced capability.

The ILRS itself does not fund the establishment or operation of ranging stations. Stations are typically associated with a host nation space or scientific research program, and are frequently located adjacent to other observatory or measurement systems.

Laser ranging stations may be a member of the ILRS network as an operational station providing data are submitted in the proper format and are of sufficient data quality to achieve IAG related objectives. Engineering stations are those that perform engineering or development work that may be of interest to the ILRS in its IAG or other science or engineering activities, or if the station is in process with the objective of supporting the ILRS in its IAG or other science objectives.

Stations must adhere to the ILRS guidelines and follow established procedures to maintain their operational status in the ILRS network. These guidelines were reviewed and documented on the ILRS website:

- Range to satellites that have been authorized by the ILRS and maintained on the ILRS website;
- Adhere to the ILRS restricted tracking procedures and only range to restricted missions when explicitly approved by the ILRS and the mission;
- Maintain site logs and configuration files, ensuring content is current;
- Maintain aircraft avoidance and other ILRS safety procedures;
- Adhere to the ILRS data product delivery requirements;
- Strive to produce the highest quality SLR measurement by:
    - Eliminating systematic errors;
    - Carrying out regular system delay calibrations;

- Regularly surveying the site reference markers and inter-technique site ties;
- Investigating and responding promptly to ILRS notifications and communications regarding data quality issues.

Stations in the ILRS network may support other science and engineering activities, but must adhere to the ILRS safety requirements above.

Stations in the ILRS Network

The stations in the ILRS network range to a constellation of approved satellites as approved by the ILRS Governing Board. Stations transmit their data on an hourly or daily basis to ILRS Operations Centers for final archive at the ILRS Data Centers. The tracking data produced by the ILRS network stations are regularly and continuously analyzed by the ILRS Analysis Centers to generate official ILRS products. The ILRS network during the 2016-2019 timeframe is shown in Figure 8-1; lists of stations (current, engineering, closed/inactive, and future) in the ILRS network are maintained on the ILRS website at: *https://ilrs.gsfc.nasa.gov/network/stations/index.html*.

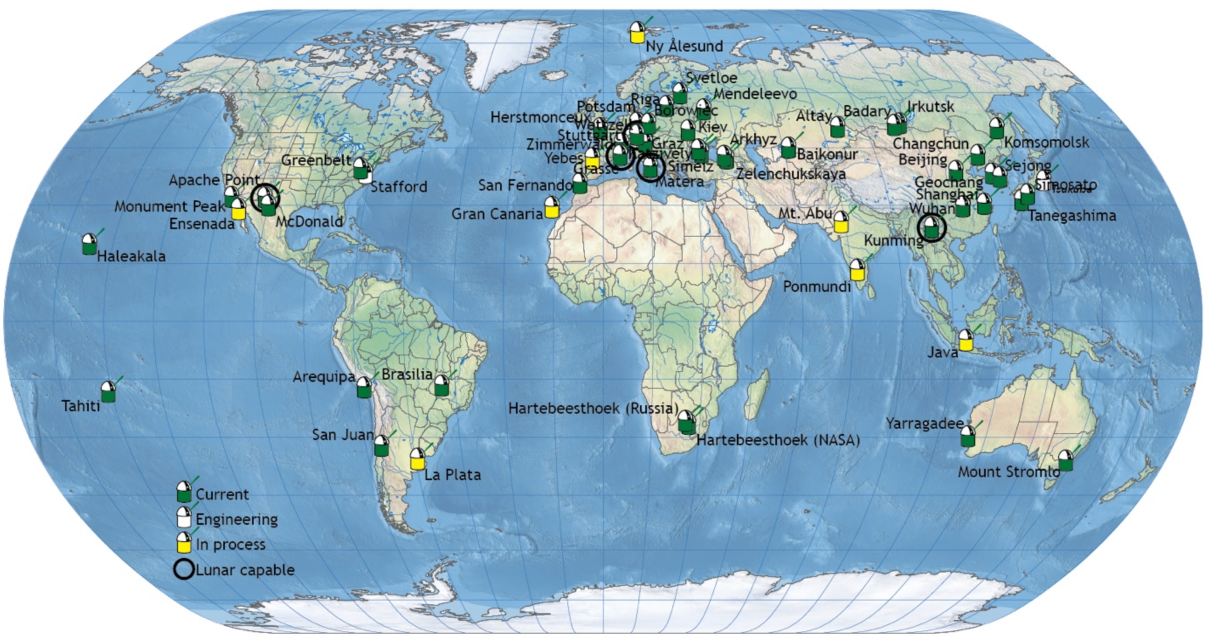

Figure 8-1. The ILRS network during the 2016-2019 timeframe.

During the 2016-2019 period, 43 stations regularly tracked 151 satellites, generating over 7.25M normal points from over 708K passes. Figure 8-2 and 8-3 plot the number of passes per station with the number of tracking days; Table 8-1 presents various tracking statistics for the reporting period. The geodetic satellites (i.e., LAGEOS and LARES) are a top priority for the network, however GNSS satellites are now playing a large role in SLR tracking.

As can be seen in these charts and table, there is a large divergence in the station performance across the ILRS network. In recent years, nearly half of the stations in the ILRS network achieved the 3500 passes/year minimum guideline. Low data yield in some cases has been due to station upgrades or technical issues, and thus the ILRS anticipates increased performance in the future. Unfortunately, stations with low performance levels contribute very little to the ILRS derived products which are incorporated into the ITRF.

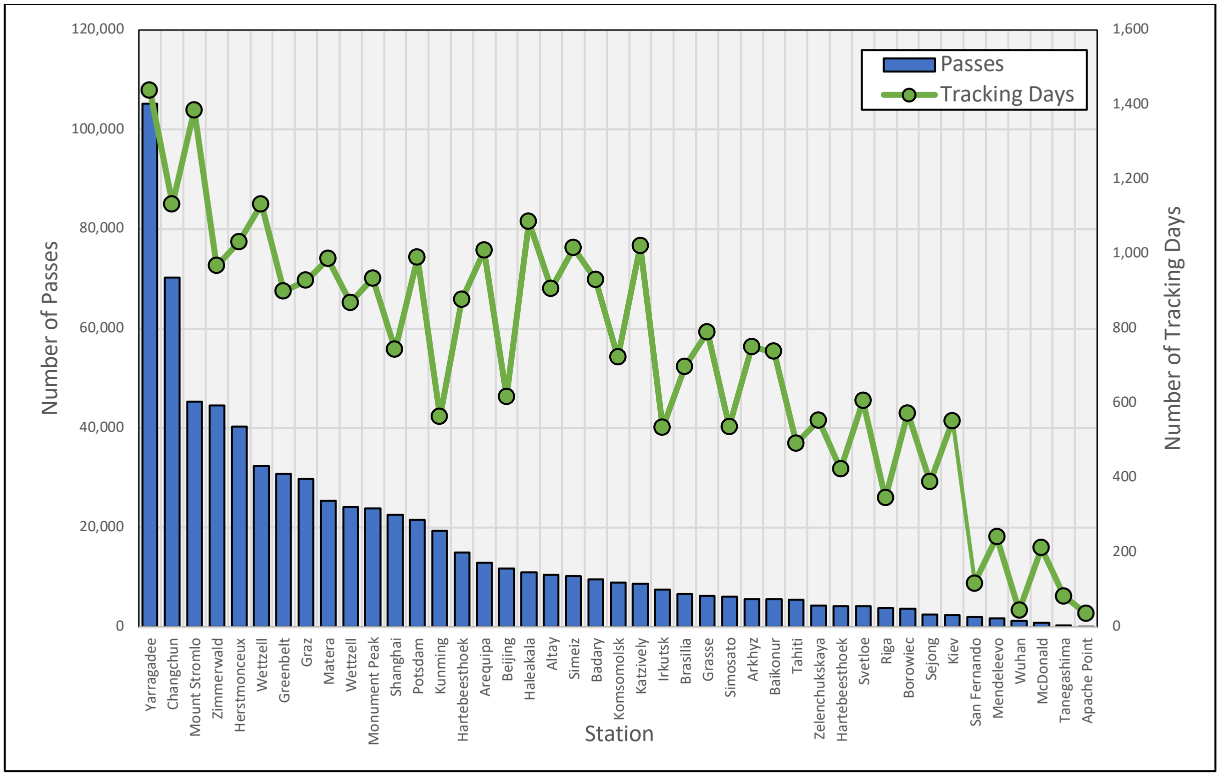

Figure 8-2. SLR pass and tracking days figures for 2016-2019.

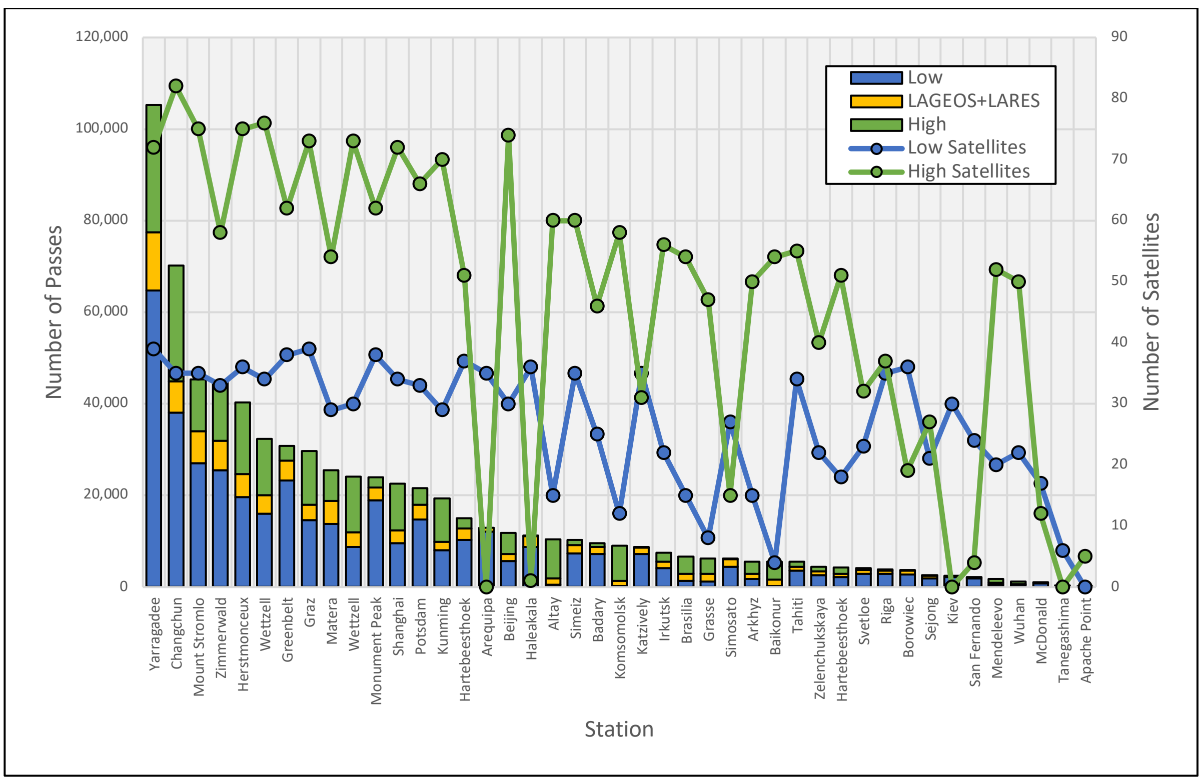

Figure 8-3. SLR pass total figures for 2016-2019.

Table 8-1. ILRS network pass totals (01-Jan-2016 through 31-Dec-2019)

Site Name	Sta.	Code	Start	End	Passes	NPTs	Satellites
Altay	1879	ALTL	160101	191228	10,415	44,440	78
Apache Point	7045	APOL	160103	161125	131	259	5
Arequipa	7403	AREL	160104	191231	12,892	129,109	38
Arkhyz	1886	ARKL	160111	191231	5,546	28,915	68
Badary	1890	BADL	160101	191226	9,541	80,406	74
Baikonur	1887	BAIL	160411	191224	5,538	21,857	61
Beijing	7249	BEIL	160301	191228	11,774	72,950	107
Borowiec	7811	BORL	160203	191231	3,674	55,615	58
Brasilia	7407	BRAL	160102	191230	6,613	23,708	72
Changchun	7237	CHAL	160101	191231	70,185	507,103	120
Golosiiv	1824	GLSL	160103	191220	2,444	19,889	33
Grasse	7845	GRSM	160107	191230	6,220	72,905	58
Graz	7839	GRZL	160101	191229	29,721	366,045	116
Greenbelt	7105	GODL	160104	191231	30,783	485,897	103
Haleakala	7119	HA4T	160101	191231	11,035	160,404	40
Hartebeesthoek (NASA)	7501	HARL	160105	191218	14,945	190,538	91
Hartebeesthoek (Sazhen-TM)	7503	HRTL	170324	191215	4,239	33,383	72
Herstmonceux	7840	HERL	160103	191230	40,312	371,437	114
Irkutsk	1891	IRKL	160122	191225	7,507	49,592	81
Katzively	1893	KTZL	160101	191230	8,679	89,754	69
Komsomolsk-na-Amure	1868	KOML	160101	191230	8,915	37,677	73
Kunming	7819	KUN2	170123	191230	19,290	131,094	102
Matera	7941	MATM	160101	191231	25,412	234,327	87
McDonald	7080	MDOL	160113	181026	885	6,064	32
Mendeleevo	1874	MDVS	160121	191125	1,773	18,710	75
Monument Peak	7110	MONL	160108	191231	23,897	366,779	103
Mount Stromlo	7825	STL3	160101	191231	45,244	467,322	113
Potsdam	7841	POT3	160103	191230	21,506	274,190	103
Riga	1884	RIGL	160404	191219	3,794	60,417	76
San Fernando	7824	SFEL	160108	191230	2,049	19,502	31
Sejong	7394	SEJL	160111	191125	2,499	29,785	52
Shanghai	7821	SHA2	160102	191231	22,565	149,558	109
Simeiz	1873	SIML	160111	191228	10,184	95,602	98
Simosato	7838	SISL	160104	191225	6,100	91,488	45
Svetloe	1888	SVEL	160101	191231	4,125	30,292	58
Tahiti	7124	THTL	160113	190530	5,451	71,975	92
Tanegashima	7358	GMSL	160419	191212	361	2,616	9
Wettzell (SOS-W)	7827	SOSW	160108	191230	24,094	151,047	106
Wettzell (WLRS)	8834	WETL	160102	191230	32,346	221,556	113
Wuhan	7396	JFNL	180929	191213	1,169	7,228	75
Yarragadee	7090	YARL	160101	191231	105,230	1,406,264	114
Zelenchukskaya	1889	ZELL	160102	190726	4,364	32,167	65
Zimmerwald	7810	ZIML	160321	191231	44,549	540,432	95
Totals	43 sta.				707,996	7,250,298	151

An Eye to the Future of the ILRS Network

The many new SLR systems in process and undergoing upgrade will significantly enhance the productivity and geographical coverage of the ILRS network. New and upgraded systems typically include higher repetition rates, increased accuracy, more automation, and state-of-the-art electronics and signal detection. Some of the recently reported network developments include:

- The BKG SLR system from Concepción has been relocated to La Plata, Argentina, and is being upgraded as part of the new Argentine-German Geodetic Observatory (AGGO) Core site. The SLR is going through its final stages of setup and is expected to be operational by late 2020 or early 2021.
- The National Astronomical Observatories of China (NAOC), Chinese Academy of Sciences (CAS) is upgrading their system in San Juan, Argentina in cooperation with the Felix Aguilar Astronomical Observatory, San Juan National University; the system is scheduled to be back in operation by early 2021.
- The Finnish Geospatial Research Institute, National Land Survey (FGI) is constructing a new SLR system at the Metsähovi Geodetic Research Station; the system is scheduled to be in operation in early 2021 as a future GGOS Core Site.
- NASA is building new generation SLR systems for deployment at: (1) Ny Ålesund, Norway (with the Norwegian Mapping Authority) a part of the new Ny Ålesund Core Site, (2) McDonald Observatory in Texas as part of the new McDonald Core Site, and (3) Hawaii as part of the Hawaii Core Site. Installations are planned for staging over the next five to six years.
- The ROSCOSMOS network is planning new systems in Ensenada, Mexico; Grand Canaria, Spain; Java, Indonesia; and other possible sites; these will be the new Tochka systems; deployment is planned over the next five to six years.
- ISRO is building new SLR stations in Mt. Abu and Ponmundi in India; these stations are planned for operation by 2022.
- The Yebes Observatory (IGN, National Geographic Institute) is designing and building the Yebes LAser RAnging (YLARA) Station. The location has been selected and work is underway. First light is expected in 2023 and routine operations in the 2024 timeframe. The site will join the two VLBI antennas, GNSS receiver, and gravimetry techniques, also operational in site, to form a Core station.
- The Geospatial Information Authority of Japan (GSI) is planning a new station for Tsukuba, Japan, in close proximity to the new VLBI station in Ishioka.

With these activities underway, the ILRS anticipates considerable improvement in network data quantity, quality and geographic coverage over the next 5 to 6 years.

ILRS Station Reports

Altay, Russia

Author: *Natalia Parkhomenko*
Responsible JC "RPC "PSI"

System: ALTL/1879
Location: Altay Territory, t. Zmeinogorsk, Russia
Latitude: 51.2°N, Longitude: 82.3°E, Elevation: 270m

Station Operations

The Altay station (ALTL/1879) is housed in the Altay Optic-Laser Center (AOLC), 300 km southwest of the city of Barnaul, 20 km to the north of town Zmeinogorsk. The NOLS TTI SLR station started operations on September 15, 2004.

Station staff strives to work on a 12/7 basis, focusing as a first priority on targets of Russian interest (e.g., GLONASS, photometry) and then on the ILRS priority list.

Figure 8-4. Location of facilities in Altay, Russia.

Figure 8-5. SLR system at Altay, Russia.

System Improvements

- Completed work to optimize algorithms and software related to the search and tracking of satellites, as well as the detection of a signal reflected from the LRA on the satellite.
- Developed and implemented a program for visualization/display of spacecraft flight paths.
- Modified the Diaphragm Switching Unit to increase the wear resistance of the field diaphragm positioning mechanism.

Current Challenges and Future Plans

Any problems with hardware and software are resolved quickly through remote consultations, and, if necessary, a specialist from PSI can visit the SLR station.

Future plans to improve the Altay SLR system include:

- Development and implementation of digital cameras with a permeability of at least 12 magnitude to replace the TV cameras that have outlived their life.
- Development and implementation of a laser with a pulse duration of not more than 60 ps.
- Development of software for calculating normal points directly at the station in order to reduce data access time for users.

Station Personnel

- Person 1: Manager of the NOLS TTI system
- Person 2: NOLS TTI operator
- Person 3: NOLS TTI operator
- Person 4: NOLS TTI operator

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Arequipa, Peru

Author: *Raul Yanyachi/Universidad Nacional de San Agustín de Arequipa*
Responsible Agency: Universidad Nacional de San Agustín de Arequipa

System: AREL/7403
Location: Observatory of Characato at University San Agustin, Arequipa
Latitude: 16.4657° S, Longitude: 71.4930° W, Elevation: 2489.05 m

Station Overview

Figure 8-6. TLRS-3 NASA station in Arequipa, with DORIS antenna in foreground and the Chachani and Misti volcanoes in the background.

The TLRS-3 NASA station is located in the Observatory of Characato at University San Agustin, Arequipa, Peru. The station continued operations during 2017 and 2018.

Figure 8-7. Panoramic views of the Arequipa site.

Station Operations

In 2017, Arequipa performed with three-shift operations (24 hours) for five days a week; a fourth shift during weekend nights (12 hours coverage) began in April 2018.

TLRS-3 tracks low orbiting satellites during the day and night with good results. Mid-altitude orbiting satellites such as LAGEOS-1 and -2 have better results during nighttime operations. TLRS-3 does not track high orbiting satellites. Figures 8-8 and 8-9 below show normal point and pass totals for 2017 and 2018.

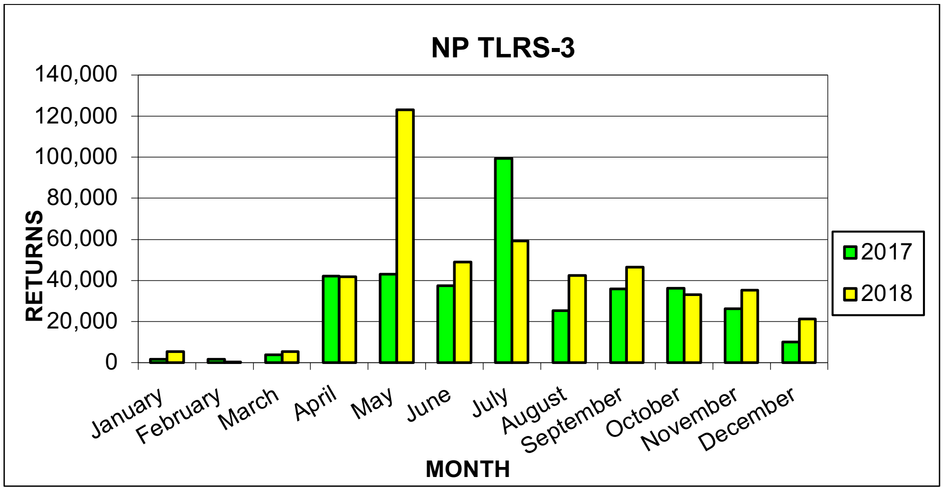

Figure 8-8. TLRS-3 normal point statistics for 2017 and 2018.

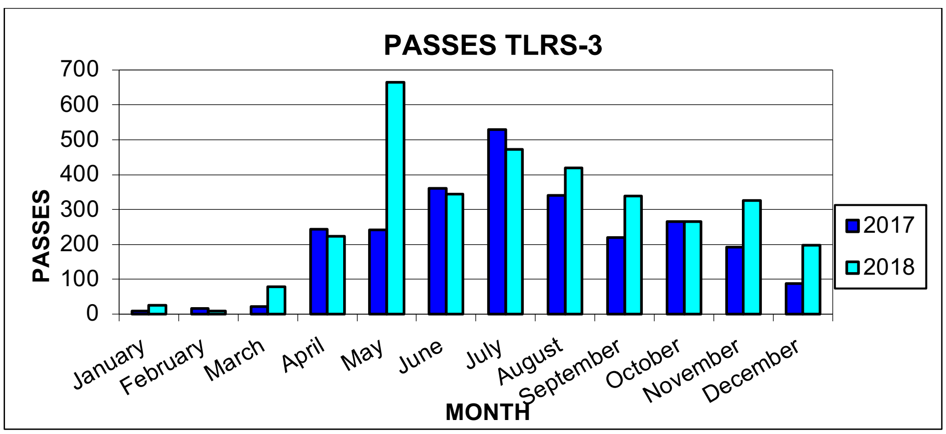

Figure 8-9. TLRS-3 pass statistics for 2017 and 2018.

System Improvements

The staff performed some important changes to the system in 2016:

- Replaced two motors in the mount (one for azimuth and other for elevation)
- Upgraded the RCC
- Removed time code generator
- Added new event timer
- Installed new MET-4

At the end of 2016, NASA engineers replaced the old T/R switch with a static T/R switch and installed a new scope. During 2017 and 2018, the system tracked LAGEOS-1 and -2 to validate the event timer installation.

Significant Events

In 2016, David McCormick, the NASA SLR Manager, and Claudia Carabajal from GSFC visited Arequipa to meet UNSA's new administration staff and discuss the continued operations of the TLRS-3 station.

Figure 8-10. UNSA Rector, David McCormick, and Claudia Carabajal during a site visit in 2016.

During the 2016-2018 time period, the station commemorated the "Day of Astronomy" with an "Open Door" visit to the Observatory, welcoming visits from students and neighbors. The station staff participated in events related to the lunar eclipse in January 2019, sponsoring several courses at IAAPP and the station, covering such topics as space geodesy techniques, use of cluster, processing satellite imagery, GAMIT software use, and others.

On April 29, 2019 Stephen Merkowitz, Rivers Lamb, and Claudia Carabajal visited the station and UNSA to discuss with UNSA's authorities the terms for renewing the agreement between their institutions for an additional five years. They signed a letter of intention, which will be validated with a new agreement. Merkowitz, Raul Yanyachi, and Carabajal gave several presentations ("NASA Space Geodesy Project", "Observatory the Characato Activities", and "ICESat-2 Mission") in the UNSA Paraninfo (Figure 8-11). Merkowitz also participated in interviews with local TV, radio, and newspapers (Figure 8-12).

Figure 8-11. Stephen Merkowitz, Claudia Carabajal, and Raul Yanyachi during the presentation at UNSA Paraninfo in April 2019.

Many visitors from local schools and universities toured the TLRS-3, with presentations by station personnel.

Figure 8-12. Rivers Lamb and Stephen Merkowitz during their interviews in Arequipa in April 2019.

Co-located Systems

UNAVCO provided a new GNSS choke ring antenna in April 2018 that is connected to the JAVAD GPS/GNSS receiver, as well as a new UPS for the equipment.

Figure 8-12. GNSS antenna installation at site.

IGN/CNES sent a new GNSS receiver (Polar 5x Septentrio) to support their REGINA project. In addition, IGN and CNES provided new equipment and a backup battery for the DORIS installation at Arequipa.

UNSA continued to host the Cluster SGI in the dark room of SAO-2 building office. The IAAPP-UNSA continued maintenance of the SAO-2 building at the station which is equipped with computers for use as a classroom and data processing center, a communication room equipped with VNA, spectrum analyzer, and signal generator for measuring antenna parameters and performing general training. A new air conditioner and network equipment were also installed in this building.

Personnel

The crew at TLRS-3 consists of:

- Dr. Raul Yanyachi, station manager
- Jorge Valverde, Manuel Yanyachi (until 2017), Mariano Gomez, senior observers
- Marco Higueras, Kevynn Rodriguez, associate senior observers (since 2018)
- Alex Sanabria, junior observer
- Christian Levita (since 2017) and Julver Galindo (since 2018), training observers
- Janet Caceres, administrative assistant
- Wilberto Cañari, maintenance assistant

Figure 8-14. TLRS-3 personnel with David McCormick/NASA (2016).

Figure 8-15. TLRS-3 personnel with Rivers Lamb/NASA (2019).

Current Challenges and Future Plans

The staff plans to implement a 10pps tracking capability and start processing GNSS and SLR data with a new scientific software package.

Contacts

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Arkhyz, Russia

Author: *Natalia Parkhomenko*
Responsible JC "RPC "PSI"

System: ARKL/1886
Location: Arkhyz vil., Karachay-Cherkess Republic, Russia
Latitude: 43.6500°N, Longitude: 41.4333°E, Elevation: 2077m

Station Operations

The Arkhyz station (ARKL/1886) is housed in the Northern Caucasus. The Sazhen-TM SLR station started operations in 2006.

Station staff strives to work on a 12/7 basis, focusing as a first priority on targets of Russian interest (e.g., GLONASS) and then on the ILRS priority list.

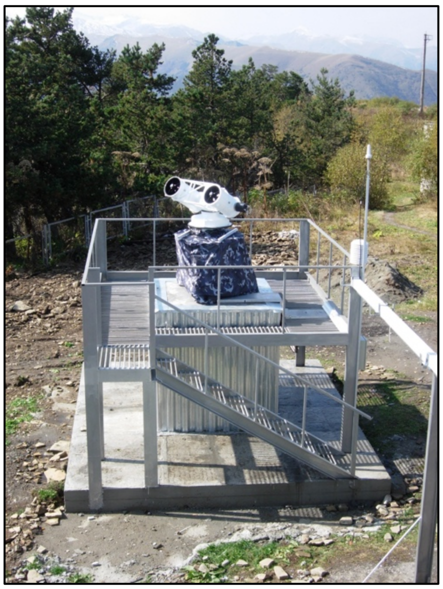


Figure 8-16. Left to right: Old and new Sazhen-TM systems located at Arkhyz, Russia.

System Improvements

- Developed and implemented a program for visualization/display of spacecraft flight paths.
- Modified the diaphragm switching unit to increase the wear resistance of the field diaphragm positioning mechanism.
- Installed and tested the second Sazhen-TM SLR system.

Current Challenges and Future Plans

Any problems with hardware and software are resolved quickly through remote consultations, and, if necessary, a specialist from PSI can visit the SLR station. There is no laser for the second Sazhen-TM system.

Future plans to improve the Arkhyz SLR system include:

- Development and implementation of digital cameras with a permeability of at least 12 magnitude to replace the TV cameras that have outlived their life.
- Development and implementation of a laser with a pulse duration of not more than 60 ps.
- Development of software for calculating normal points directly at the station in order to reduce data access time for users.

Station Personnel

- Person 1: Manager of the Sazhen-TM system
- Person 2: Sazhen-TM operator
- Person 3: Sazhen-TM operator

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Badary, Russia

Authors: *Iskander Gayazov, Viktor Mitryaev*
Responsible Agency: Institute of Applied Astronomy (IAA RAS)

System: BADL/1890
Location: Republic of Buryatia, Russian Federation
Latitude: 51.7700°N, Longitude: 102.2354°E, Elevation: 803 m

Station Operations

The Badary SLR station (BADL/1890) is located in Badary (Republic of Buryatia, Russian Federation) at one of three observatories in the “Quasar-KVO” VLBI network. The observatory is a co-location site with two radio telescopes (RT-32 and RT-13), “Sazhen-TM” SLR system, GNSS receiver, DORIS antenna, and water vapor radiometer. The SLR system has day and night cameras and a holographic filter (0,1 nm bandpass) which allows for all day operations. In spite of a relatively small aperture telescope (25 cm) and low pulse energy (2,5 mJ), the laser system is capable of conducting observations of satellites with orbits up to 40000 km.

Figure 8-17. “Sazhen-TM” SLR system (left) and the laboratory equipment of the laser system (right).

Figure 8-18. GNSS antenna, DORIS antenna and RT-32 radiotelescope.

System Improvements

In 2018, new star calibration software was installed at the station. This software allows the staff to make angular corrections automatically and improves tracking capabilities enormously, especially in the daytime.

Current Challenges and Future Plans

The main problem is the obsolescence of the laser emitter of the system. This leads to the need to repair the laser every few years. The current laser has a pulse width worse than 300 ps. This is the main reason for the current level of single shot RMS (3-4 cm). The main task for the future is to modernize the system and improve the RMS up to 1 cm. To reach this goal, a replacement of the laser with new equipment is in planning stages, which has a ~50 ps pulse width. The next step is to replace the time interval counter and to increase the repetition rate from 300 Hz up to 600 Hz. These plans are expected to be implemented after 2020.

Station Personnel

The laser system at the observatory is maintained by a staff of operators, who work in shifts (two operators per shift). All operators are capable to carry out both VLBI and SLR observations even if they occur at the same time. The observation results are sent via network transmission to the processing center at IAA (Saint-Petersburg). There, the data are processed and sent to EDC and other users. Repairs of the system and overall operation are conducted by the lead engineer Viktor Mitryaev.

The station operators are as follows:

- Anna Zhiritskaya
- Olesya Alakova
- Veronika Lysakova
- Oksana Plotnikova
- Olga Slepkova
- Dmitry Zadrutski
- Tatiana Kotlova
- Aleksander Sorokovikov

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Baikonur, Kazakhstan

Author: *Natalia Parkhomenko*
Responsible JC "RPC "PSI"

System: BAIL/1887
Location: Baikonur, Kyzylorda region, Kazakhstan
Latitude: 45.7046°N, Longitude: 63.3422°E, Elevation: 98.3m

Station Operations

The Baikonur SLR system is located in the territory of the Baikonur cosmodrome. The Sazhen-TOS station started operations in 2006.

Station staff strives to work on 8/7 basis, focusing as a first priority on targets of Russian interest (e.g., GLONASS) and then on the ILRS priority list.

Figure 8-19. SLR system located in Baikonur, Kazakhstan.

System Improvements

- Developed and implemented a program for visualization/display of spacecraft flight paths.
- Modified the Diaphragm Switching Unit to increase the wear resistance of the field diaphragm positioning mechanism.

Current Challenges and Future Plans

Any problems with hardware and software are resolved quickly through remote consultations, and, if necessary, a specialist from PSI can visit the SLR station.

Future plans to improve the SLR system Baikonur:

- Development and implementation of digital cameras with a permeability of at least 12 magnitude to replace the TV cameras that have outlived their life.
- Development and implementation of a laser with a pulse duration of not more than 60 ps.
- Development of software for calculating normal points directly at the station in order to reduce data access time for users.

Station Personnel

- Person 1: Manager of the Sazhen-TOS system
- Person 2: Sazhen-TOS operator
- Person 3: Sazhen-TOS operator

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Borowiec, Poland

Author: *Dr. Pawel Lejba/CBK*
Responsible Agency: Centrum Badań Kosmicznych Polskiej Akademii Nauk (CBK PAN) – Space Research Centre of the Polish Academy of Sciences (SRC PAS)

System: BORL/7811
Location: Astrogeodynamic Observatory Borowiec
Latitude: 52.2770° N, Longitude: 17.0746° E, Elevation: 123.4 m

Station Operations

The SLR station in Borowiec (site acronym BORL, station number 7811) is an active station in the ILRS network, located near Poznan, Poland. The station performs nighttime tracking all-year round including weekends.

Figure 8-20. The Borowiec system building.

System Improvements

Recent system developments at Borowiec include:

- Observations of active satellites (LEO-MEO regime) and space debris (including cooperative and uncooperative targets) from LEO regime by means of two independent laser modules (ps and ns)
- ADS-B monitoring
- Additionally, new format of laser data TDM (Tracking Data Message, recommended standard CCSDS 503.0-B-1, *https://public.ccsds.org/Pubs/503x0b1c1.pdf*)

The main problems for the system are the limited range of measurements (up to 23000km) and the inability to perform daylight tracking.

Current Challenges and Future Plans

The current technical challenges and future plans for the station over the next two years include:

- Day tracking (2020)
- Tracking 24/7 (2020)
- Installation of event timer (2019)
- Measurements in the range from 300 up to 40000km (2019)
- New detection system (2020)

Station Personnel

The Borowiec station staff members are as follows:

- Dr. Paweł Lejba, manager
- Dr. Eng. Tomasz Suchodolski, main engineer
- MSc. Piotr Michałek, technician-observer
- Stanisław Zapaśnik, technician-observer
- MSc. Jacek Bartoszak, supporting technician
- Prof. Stanisław Schillak, supporting mentor

Figure 8-20. Borowiec station staff (left to right): Pawel Lejba, Tomasz Suchodolski, Jacek Bartoszak, Piotr Michalek, Stanislaw Zapasnik.

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Brasilia, Brazil

Authors: *Natalia Parkhomenko, Geovany A. Borges, Renato A. Borges*
Responsible JC “RPC “PSI”/University of Brasilia (UnB)

System: BRAL/7407
Location: Brasilia, Brazil
Latitude: 15.7731°S, Longitude: 47.8653°W, Elevation: 1029.24m

Station Operations

The Brasilia station (BRAL/7407), a Russian Sazhen-TM SLR system, is located at the Campus Universitário Darcy Ribeiro, Asa Norte, Brasilia-DF, CEP: 70.910-900, Brazil. The construction of the Sazhen-TM station started during 2014 and the first ranging session took place in May 2014. In August 2018, the International Laser Ranging Service (ILRS) accepted the station as a contributing system to the ILRS network.

The station staff strives to work on a 24/7 basis, focusing, as a first priority, on targets of Russian interest (e.g., GLONASS) followed by satellites on the ILRS priority list.

Figure 8-22. SLR system in Brasilia, Brazil.

System Improvements

Work was done to optimize software algorithms related to the search and tracking of spacecraft, the detection of a signal reflected from the spacecraft, as well as for visualization/display of spacecraft flight paths.

Current Challenges and Future Plans

Various system hardware issues were experienced along these years of operation, negatively impacting the data yield. Nevertheless, these problems have been solved ensuring the station is in excellent working order with a high level of functionality.

Some future plans include:

- Improvement of the system of drying of optical surfaces of lenses.
- Improvement of the diaphragm switching unit to improve the wear resistance of the field diaphragm positioning mechanism.
- Development and implementation of digital cameras with a permeability of at least 12 magnitude to replace the TV cameras that have outlived their life.
- Development and implementation of a laser with a pulse duration of no more than 60 ps.

Figure 8-23. SLR telescope and operations room at Brasilia, Brazil.

Station Personnel

- Geovany A. Borges: Coordinator of the Sazhen-TM system and group
- Renato A. Borges: Vice-Coordinator of the Sazhen-TM system and group
- Francisco Assis Lima: Sazhen-TM technical support
- Luis Fernando Dias Pinheiro Soares: Sazhen-TM operator
- Raniere Rodrigues de Oliveira: Sazhen-TM operator
- Rogério Rocha Peixoto: Sazhen-TM operator
- Justino Cardoso Mendonça: Sazhen-TM operator
- Carlos Antônio de Aquino Bezerra: Sazhen-TM operator
- Maria Eliene Ferreira Linhares Côrtes: Sazhen-TM operator
- Silvério Alan Lima da Silva: Sazhen-TM operator

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Changchun, China

Authors: *Han Xingwei, Dong Xue, Liang Zhipeng*
Responsible Agency: Changchun observatory of National Astronomical Observatory, Chinese Academy of Sciences

System: CHAL/7237
Location: JIngyuetan Park xishan Changchun, P.R. China
Latitude: 43.7905° N, Longitude: 125.4434° E, Elevation: 274.9 m

Station Operations

Hours of operation: Weekdays: 24 hours
Status of station: Operational

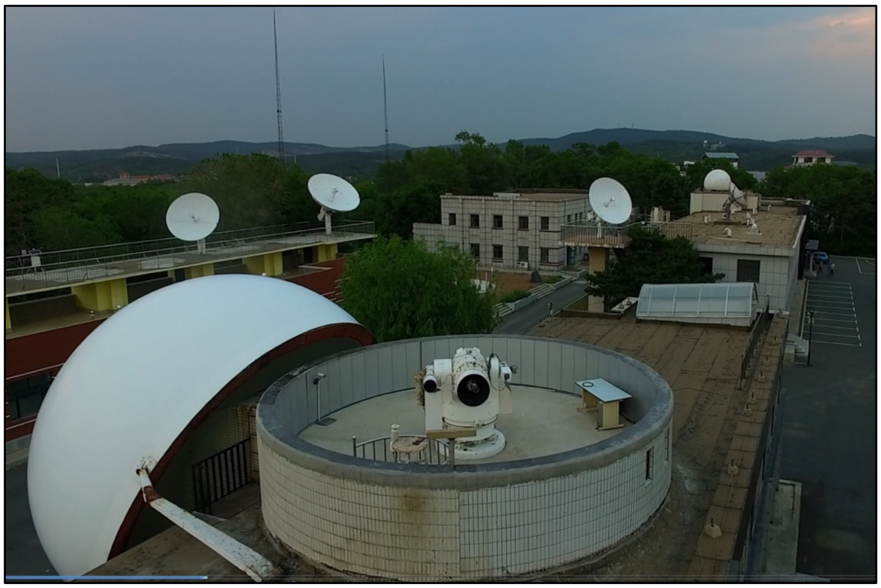

Figure 8-24. Changchun laser ranging station.

System Improvements

- Space debris laser ranging with a 60mJ @532nm/500Hz laser
- Improvement of daylight ranging to GNSS
- Improvement in data quality of Changchun high repetition rate laser ranging system
- A thermostatic housing for C-SPAD was installed to keep the temperature around detector stable, so as to avoid temperature drift effect for system delay.

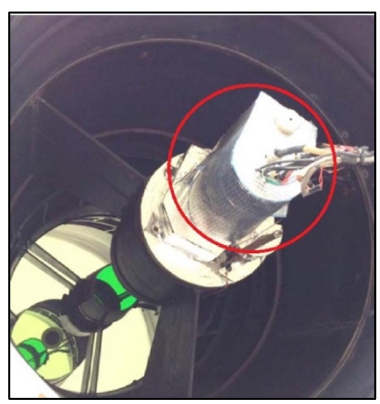

Figure 8-25. Thermostatic housing for C-SPAD.

Current Challenges and Future Plans

- Space debris laser ranging with 1064nm laser
- Light curve detection with SPAD detectors
- Improvement in data quality of Changchun
- Automation of the SLR observations

Station Personnel

- Fan Cunbo: Group leader, scientist
- Han Xingwei: Group leader, scientist, project management
- Dong Xue: Software, scientist, project management
- Song Qingli: Laser, engineer, station operations
- Liang Zhipeng: Engineer, scientist, data analysis
- An Ning: Engineer, scientist
- Wen Guanyu: Optics, scientist
- Gao Jian: Electronic, scientist
- Zhao Guohai: Mechanical, observations
- Zhang Haitao: Engineer, observations

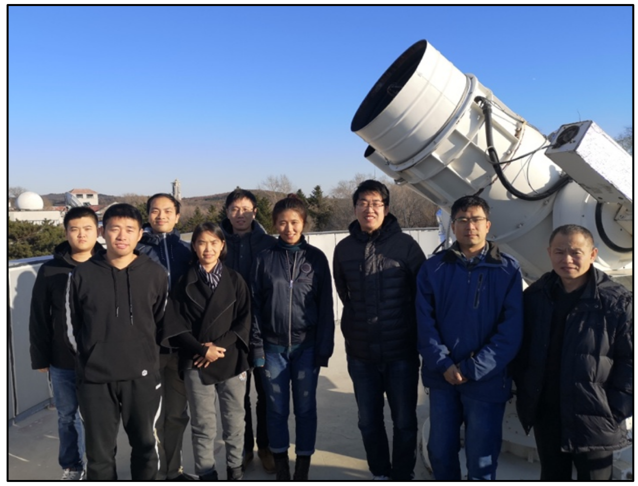

Figure 8-26. Changchun SLR station staff.

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Geochang, Republic of Korea

Author: *Hyung-Chul Lim*
Responsible Agency: Korea Astronomy and Space Science Institute (KASI)

System: GEOL/7395
Location Mt. Gamak, Geochang-gun, Gyeongsangnam-do, Republic of Korea
Latitude: 35.5902° N, Longitude: 127.9201° E, Elevation: 934.063 m

Station Operations

The Korea Astronomy and Space Science Institute has been developing the space optical and laser tracking (SOLT) system for space geodesy, space situational awareness, and Korean space missions. The SOLT system was established on Mt. Gamak at Geochang county, about 950 m high above sea level to improve the quality of satellite images achieved from the adaptive optics, which consists of satellite laser ranging (SLR), adaptive optics (AO), and debris laser tracking (DLT) systems. The SLR and AO system had been developed in the end of 2017 but the SLR system is still in the experimental stage due to the unstable laser system in terms of pulse energy. The DLT system is designed to provide angular measurements as well as range data of space debris because of the high tracking accuracy of the telescope, which is currently under development.

Figure 8-27. Geochang SOLT station.

System Improvements

The Geochang system has the common coudé optical path using a 100 cm telescope, which is designed to be capable of laser ranging up to geosynchronous Earth orbit satellites with a laser retroreflector array, space objects imaging brighter than magnitude 10, and laser tracking low Earth orbit space debris of uncooperative targets. For the realization of multiple functions in a novel configuration, the Geochang system employs a switching mirror that is installed inside the telescope pedestal and feeds the beam path to each system (i.e., SLR, AO, and DLT).

The laser system consists of four modules: mode-locked laser oscillator, regenerative amplifier, power amplifier, and second harmonic generation. The laser has 15 mJ of pulse energy and 9 ps of pulse width. The laser beam size is expanded 21 times by two beam expanders in the transmitting optics and 3 times in the telescope. The clear apertures are 100 and 25 cm for the primary mirror and secondary mirror, respectively. The telescope focus is automatically controlled with 10 µm accuracy against the thermal expansion of telescope based on the temperature measurement of the optical tube assembly (OTA) and compensation by the primary/secondary mirror spacing. The tracking mount has a large hollow shaft for the optical beam path of 30 cm diameter, which is of the alt-azimuth type. It is required to be controlled fast and accurately to track LEO space debris, even at an altitude of 200 km. The tracking mount moves very fast with the slew rate of 30 degree/sec for azimuth and 15 degree/sec for elevation and acceleration of 10 degree/sec^2 for azimuth and 5 degree/sec^2 for elevation. To realize this requirement, two arc motors with a maximum torque of 3,900 Nm for azimuth and 1,068 Nm for elevation were specifically developed and implemented.

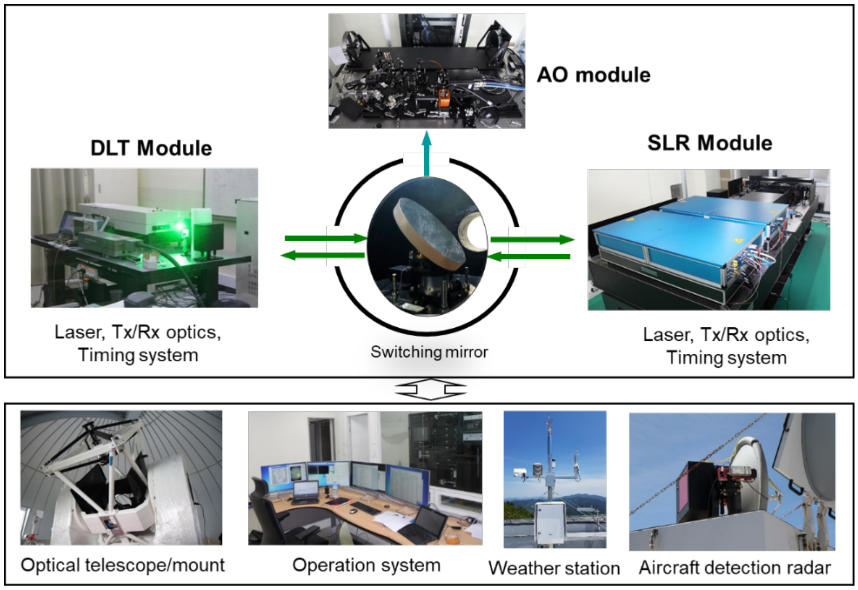

Figure 8-28. Configuration of the Geochang station.

Current Challenges and Future Plans

The single-shot precision of the Geochang SLR system was 3.6 mm for the ground target, 5.3 mm for the Starlette satellite, and 7.1 mm for the LAGEOS-2 satellite, on August 2018. But the SLR system has a fatal problem that the laser energy decreases rapidly as time goes on. After the problem is fixed, it is expected that the Geochang station plays an important role in Korean space missions as well as ILRS tracking network.

Station Personnel

- Mansoo Choi (Project Manager)
- Seung-Yeol Yu (Optical Engineer)
- Eunseo Park (Scientist of Data Processing)
- Ki-Pyoung Sung (Software Engineer)

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Golosiiv, Ukraine

Author: *Mykhaylo Medvedskyy*
Responsible Agency: Main Astronomical Observatory of NAS of Ukraine

System: GLSL/1824
Location: Kyiv, Ukraine
Latitude: 50.3633° N, Longitude: 30.4961° E, Elevation: 212.9 m

Station Operations

The station is located in Kiev on the Eurasian plate. Observations are carried out only in the nighttime during the year. The station was active during 2016-2019. In particular, during 2019, the station operated normally where a total of 878 successful observation sessions were performed, of which 72 were to the LAGEOS satellites.

System Improvements

The accuracy of a single measurement in the initial period was 8 cm. In 2018, a full upgrade of the station's hardware and the subsequent station software upgrade began and continued during 2019.

Hardware:

- Developed a time gate generator for the epoch timer with a time resolution of 40 ns, which includes:
    - GPS receiver + ATmega8
    - UTC clock with a scale resolution of 40 ns
    - Two frequency multipliers: input 5MHz, output 10MHz and 50 MHz + frequency distributors
    - 1pps generator
    - Time gate generator (40 ns step)
    - PC communication microcontroller using COM-port
    - High-speed START and STOP signal control logic
- Installed in the system event timer A033.
- Installed a fully upgraded dome control system (electric motor and control electronics).
- Fabricated and installed an automatic weather station into the system.
- Installed new rubidium frequency standard.
- Designed and created a lidar model, including software, based on a laser station. A distinctive feature is the ability to determine the intensity of the backscattering of a laser pulse at distances from some meters to tens of kilometers with the possibility of accumulating results. The spatial resolution is 15m.
- Developed a prototype of an automatic meteorological station with associated software. Characteristics of the developed meteorological station are as follows: measurement accuracy: temperature ± 0.2C, relative humidity ± 1%, atmospheric pressure ± 0.2MB; data update period 10 seconds.
- Automated the calibration process, which allowed to improve the stability and absolute accuracy of measurements.

Software:

- Created software to work with the new time gate generator and event timer A033. New software works under OS Windows. The whole complex includes 5 PCs, which are interconnected by a local network.
- Developed software for detecting aircraft using a sdr-rtl receiver. However, this software is not yet included in the station system.

The modernization made it possible to significantly reduce the time between the end of the observation and sending the results to the EDC. Now this time is a few minutes.

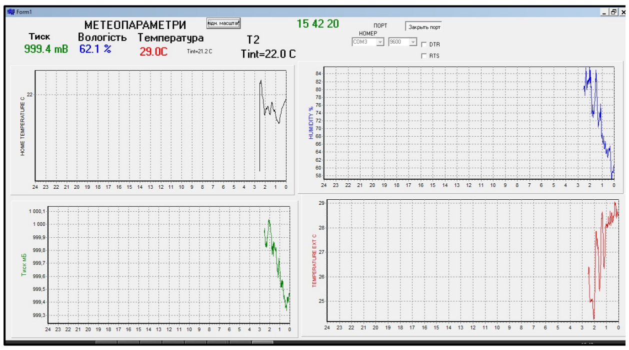

Figure 8-29. Golosiiv weather station screen.

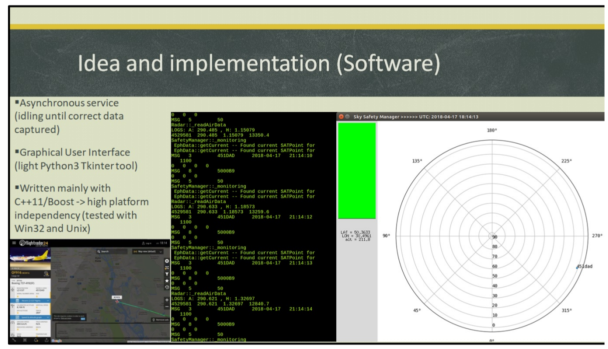

Figure 8-30. System screen shots showing recently developed software.

Main problems:

- Low measurement accuracy associated with the use of slow PMT.
- Poor quality mechanics of the telescope practically does not allow for the observation of invisible satellites.
- Poor quality of the telescope main mirror coating. There is no possibility to update the mirror coating.

Current Challenges and Future Plans

- Create new software for telescope control running Windows OS
- Design and manufacture a receiving channel using SPAD receivers
- Upgrade software that will allow observation of high satellites

Station Personnel

The Golosiiv station staff consists of three people:

- Mykhaylo Medvedskyy: Station management, development and manufacture of electronic modules, software development, including software for microcontrollers, making observations.
- Viktor Pap: Software development, making observations.
- Yurij Hluschenko: Development of electronic modules, making observations.

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Grasse, France

Authors: *Clément Courde, Julien Chabé, Hervé Mariey*
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System: GRSM/7845
Location: Observatoire de la Côte d'Azur, 2130 Route de l'Observatoire, 06460 Caussols, FRANCE
Latitude: 43.7546° N, Longitude: 6.9216° E, Elevation: 1323.1 m

Station Operations

The Grasse MeO (GRSM 7845) SLR system is located in the Grasse highlands, on the Calern site of the Observatoire de la Côte d'Azur (OCA).

Figure 8-31. The Grasse laser ranging station.

The hours of operation at Grasse are 5 of 7 days per week, 24 hours per day (3 8-hour shifts): one operator during the day, one operator during the first part of the night, one operator during the second part of the night).

The Grasse SLR system operations are divided into four main tasks: maintenance, service, research and development, and SLR/LLR observations. The system's target priorities are as follow:

- LLR to the five retroreflectors on the Moon (Apollo II, 14, 15, and Luna 17, 21)
- Geodetics satellites (LAGEOS-1, -2, LARES, Stella, Ajisai, Etalon-1, -2)
- GNSS constellations (Galileo, GLONASS, Compass)

System Improvements

Highlights:

- Time Transfer by Laser Link (T2L2)
- IR detection for LLR observation
- Optical telecommunication (with CNES, NICT, NASA, DLR)
- Two-way laser ranging on LRO (NASA, OP-SYRTE)

System developments:

- High count rate laser ranging
- Improvement of the station settings with impact on the LLR results

Current Challenges and Future Plans

The strategy of the team is oriented over three main tasks:

- The improvement of the metrological performances of the instrument in order to reach a millimetric accuracy. Two technical challenges are led: the laser ranging at high repetition rate and at two colors in single photon mode; the development and the use of optical telecommunications for the geodesy and the time transfer.
- The automation of the SLR observations: aircraft safety, thermal imagery for the cloud cover.
- The support for the development of a new SLR station in Tahiti, French Polynesia.

Future plans:

- Participation in the ACES-ELT experiment.

Station Personnel

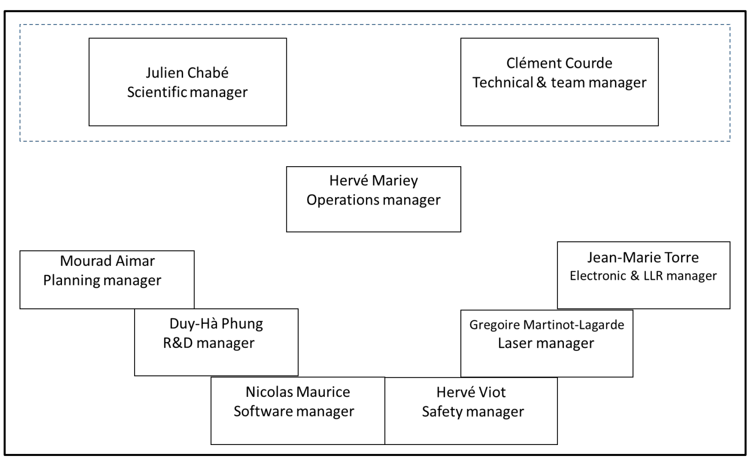

Figure 8-32. Station personnel supporting Grasse operations; staff also includes one non-permanent staff member, Julien Scariot.

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Graz, Austria

Author: *Michael Steindorfer*
Responsible Agency: Space Research Institute, Austrian Academy of Sciences

System: GRZL/7839
Location: Lustbühelstraße 46, 8042 Graz, Austria
Latitude: 47.0678° N, Longitude: 15.4942° E, Elevation: 495 m

Station Operations

Hours of operation: Weekdays: 24 hours
Status of station: Operational

Figure 8-33. Nighttime operations at the Graz Austria SLR station ranging.

System Improvements

- Space debris laser ranging
- Laser ranging up to geostationary orbit using a µJ laser
- Attitude determination of Galileo satellites
- Laser ranging without Coudé path
- Light curve detection with SPAD detectors
- Simultaneous space debris laser ranging and light curve detection to upper stage rocket bodies
- Stare and chase, pointing determination, orbit calculation and space debris laser ranging within one pass
- Design and development of laser package and detector package for ESA SLR station Tenerife

Current Challenges and Future Plans

- Space debris laser ranging during daylight
- MHz laser ranging
- ps laser ranging to space debris and cooperative targets, with one laser for both operation modes

Station Personnel

- Georg Kirchner: group leader, scientist, project management
- Michael Steindorfer: post-doc, scientist, project management
- Franz Koidl: engineer, scientist, station operations
- Peiyuan Wang: engineer, scientist, data analysis
- Reinhard Stieninger: engineer, daylight observations
- Christian Graf: daylight observations

Contacts

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AUSTRIA

Greenbelt MD, USA

Author: *Maceo Blount*
Responsible Agency: NASA GSFC

System: GODL/7105
Location: Greenbelt, MD, USA
Latitude: 39.0206° N, Longitude: 76.82770° W, Elevation: 19.184 m

Figure 8-34. MOBLAS-7 located at GGAO in Greenbelt MD.

Station Operations

The MOBLAS-7 station is located at the Goddard Geophysical and Astronomical Observatory (GGAO), NASA GSFC in Greenbelt, Maryland. The station is operational, with three shifts, 24 hours a day, five days a week. The station staff also assists the NASA engineering section in testing and upgrades for the NASA SLR tracking network.

System Improvements

- Installed the event timer (ETM) into the system in July 2016 improving the RMS by 2mm; the rate was also increased on LAGEOS from 5pps to 10pps.
- Supported the testing/verification of additional ETM systems being implemented throughout the NASA network.
- Installed a modified Laser Ranging Control (LRC) board for 10pps tracking of HEO satellites.
- Upgraded the processor computer to CentOS 6 to comply with IT security standards.
- Installed the GLM Sacher laser and a fiber optic cable to track the GOES-16 and -17 satellites for the NOAA-NASA Geostationary Operation Environmental Satellite-R (GOES-R) Series Campaign in the fall of 2017 and 2018. MOBLAS-7 and MOBLAS-4 simultaneous tracked GOES-16 and -17; the mission gave both system certificates and accolades for an outstanding campaign.
- Modified the location and height of the MET-4 sensor in line with the telescope elevation and away from the trailer for accurate meteorological data.

- Completed harmonic drive modification/upgrade in the radar as part of a Laser Hazard Reduction System (LHRS) improvement. Additional processes and procedures were put in place to ensure the radar is always aligned with the telescope.

Current Challenges and Future Plans

MOBLAS-7 staff will continue to assist the engineering section in keeping the other stations in the NASA network operational until the SGSLR systems are deployed. The Greenbelt station also plans to enter into a new campaign for the GOES-16 and -17 satellites in the fall of 2019.

Challenges faced by the station are mainly due to the ability to maintain operability of obsolete parts and equipment; however sustaining engineering is taking on multiple efforts to procure, test, and evaluate replacement solutions, such as:

- Low signal loss and more durable PMT cables.
- Stanford Research Systems FS740 to replace the XL-DC.
- Laser Power Supply and Start Diode replacements.
- Improvement of heating, air, and ventilation system.
- Procurement of spare tachometer generator and brush-rings.

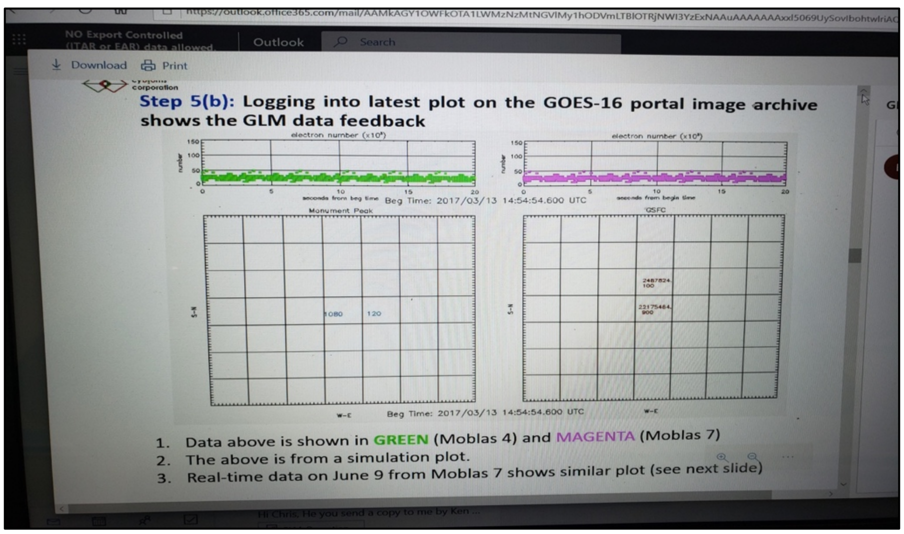

Figure 8-35. GLM support from the Greenbelt SLR station.

Station Personnel

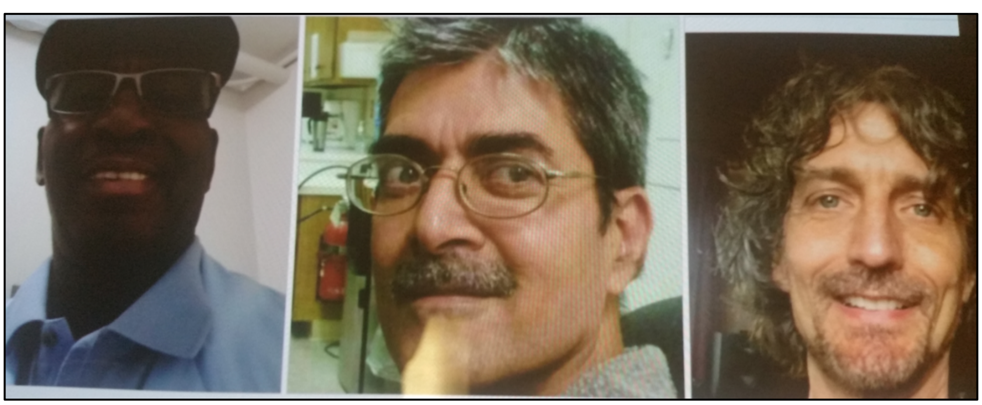

Figure 8-36. MOBLAS-7 staff (left to right): Maceo Blount; Tushar Ulja, Paul Beckwith.

The crew members track over fifty satellites during operational shifts. In addition, they perform preventive and regular maintenance of the station during the work week. The station staff members are:

- Paul Beckwith, station operator
- Tushar Ujla, station operator
- Maceo Blount, station supervisor, operations, and engineering support team
- Ken Tribble, engineering technician/operator
- Dennis Chase, lead engineer
- Jason Laing, data operations lead
- Christopher Szwec, SLR project manager

Contacts

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Haleakala HI, USA

Author: *Daniel O'Gara*
Responsible Agency: University of Hawai`i Institute for Astronomy

System: HA4T/7119
Location: Haleakala, Maui, HI, USA
Latitude: 20.7068° N, Longitude: 156.2568° W, Elevation: 3056.272 m

Station Operations

TLRS-4 is located near the summit of Haleakala on the island of Maui in the state of Hawai`i, USA. The TLRS-4 system is operated by the University of Hawai`i Institute for Astronomy under contract to NASA GSFC, and is part of the NASA Space Geodesy Network.

Tracking operations are scheduled seven days a week. There are two crews that each work 4x10 hour shifts per week for a total of eight shifts per week. Because TLRS-4 does not have an on-site radar, each crew is comprised of an observatory operator and a plane spotter. Shift start times are gradually moved over a four-week interval so that start times will move from 06:30 a.m. to 02:15 p.m. HST.

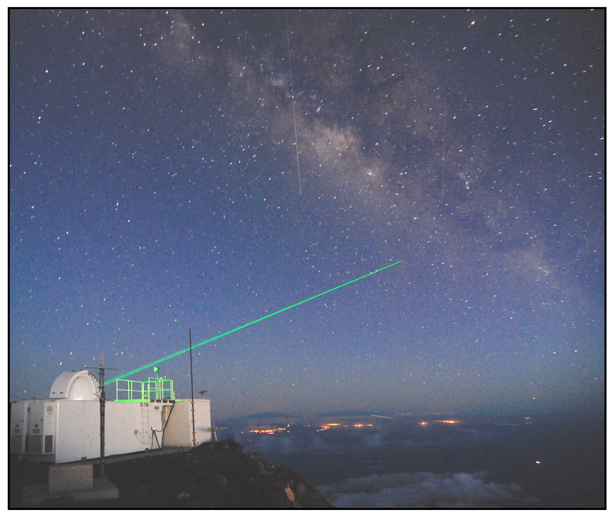

Figure 8-37. Photos of TLRS-4 system at Haleakala, HI.

System Improvements

- System accuracy was improved significantly over the last few years with the installation of a new time of flight measurement device. A Cybioms Event Timer replaced the HP5370B Time Interval Unit (TIU) on October 19, 2017. Calibration RMS improved from an average of 5.0 mm using the TIU to 2.6 mm using the Event Timer. LAGEOS-1/-2 RMS improved from an average of 10.8 mm to 8.6 mm. (See plots in Figure 8-38).
- The laser chiller was moved from inside TLRS-4 to an adjacent cinder block building, with operations restarting on June 7, 2017 after a one-day move and installation. Moving the chiller out of the TLRS-4 facility has helped us to maintain a stable interior temperature that has made for more stable laser operations. As a side benefit, the noise level inside the TLRS-4 trailer has been greatly reduced.

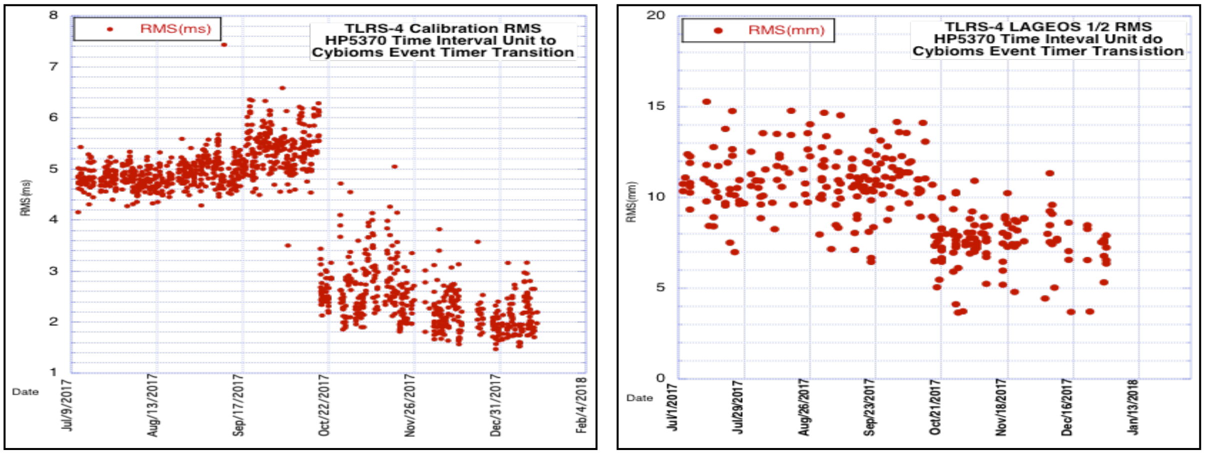

Figure 8-38. Improvements in TLRS-4 calibration and LAGEOS-1/-2 RMS after installation of event timer.

Current Challenges and Future Plans

Haleakala is planned to host an SGSLR station in the near future. To that end, multiple high performance GNSS receivers on Haleakala (and the VLBI station at Koke`e Park, Kauai) have been installed over the last two years in order to test precise site tie measurements between the two islands.

Station Personnel

Figure 8-39. Haleakala station personnel (left to right): Dan O'Gara, station manager/operations; Craig Foreman, laser technician/observatory foreman/operations; Jake Kamibayashi/electronics technician/operations; Rob Ratkowski, plane spotter/laser Ranging Safety; James Petruzzi, plane spotter/laser ranging safety.

Contact

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Hartebeesthoek, South Africa (MOBLAS-6)

Authors*: Willy Moralo, Roelf Botha*
Responsible Agency: SARAO/NASA GSFC/Peraton

System: HARL/7501
Location: Hartebeesthoek, South Africa
Latitude: 25.8897° S, Longitude: 27.6861° E, Elevation: 1406.822 m

Station Operations

The Hartebeesthoek (HARL 7501) NASA MOBLAS-6 system is located at the South African Radio Astronomy Observatory (SARAO), Hartebeesthoek facility, in near proximity to the 26-meter VLBI antenna, the HRAO GNSS reference station, and the Sazhen-TM SLR system. It has been in operation since 2000.

Station operation hours: 24hours 5 days a week and 16 hours 2 days a week.

System Improvements

Improvements:

- System slip rings replaced
- Timing system upgraded
- System air condition repaired
- System water chiller repaired

Problems:

- System radar has intermittent issues
- System MPACS (servo system is old and regularly causes problems)
- System will benefit from a better receive package (PMT tube)
- Day-time tracking is very difficult

Current Challenges and Future Plans

Current technical challenges:

- Servo system needs to be upgraded or charged for better pointing and accuracy
- Daylight tracking is almost impossible due to a poor receive package (low signal-to-noise ratio)
- System Radar need repairs
- System air conditioner are shutting down during hot summertime

Future plans for the station over the next two years,

- Upgrade servo system or replace them
- Negotiations are in process on how to improve our receive package (similar to MOBLAS-5)
- Peraton engineering personnel is visiting the station during July 2019
- Day-time camera upgrade planned
- Considering moving operations over to 24/7 pattern

Station Personnel

List of station personnel:

- Roelof Botha: Manager, Geodesy
- William Moralo: Operations supervisor
- Tshepo Makate: Technical operator
- Klaas Ramaoka: Technical operator
- Tshiamo Motlele: Technical operator

Contacts

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	Krugersdorp	Website:	*http://www.hartrao.ac.za*
	SOUTH AFRICA		

Hartebeesthoek, South Africa (Sazhen-TM)

Authors: *Roelf Botha, Andrey Pavlov*
Responsible Agency: JC "RPC "PSI"/SARAO Geodesy Programme

System: HRTL/7503
Location: Hartebeesthoek, South Africa
Latitude: 25.8892° S, Longitude: 27.6861° E, Elevation: 1413.999 m

Station Operations

The Hartebeesthoek HRTL 7503 station, a Russian Sazhen-TM SLR system, is located at the South African Radio Astronomy Observatory (SARAO), Hartebeesthoek facility, in near proximity to the 26-meter VLBI antenna, the HRAO GNSS reference station and the MOBLAS-6 SLR system (Figure 8-39). The construction of the Sazhen-TM station started in 2016 and first light was achieved on the evening of December 16, 2016. During 2017, the station started operations with a small staff complement and reached full operational status (with a full staff complement) by May 2018. On May 03, 2018 the ILRS accepted the station as a contributing system to the ILRS network.

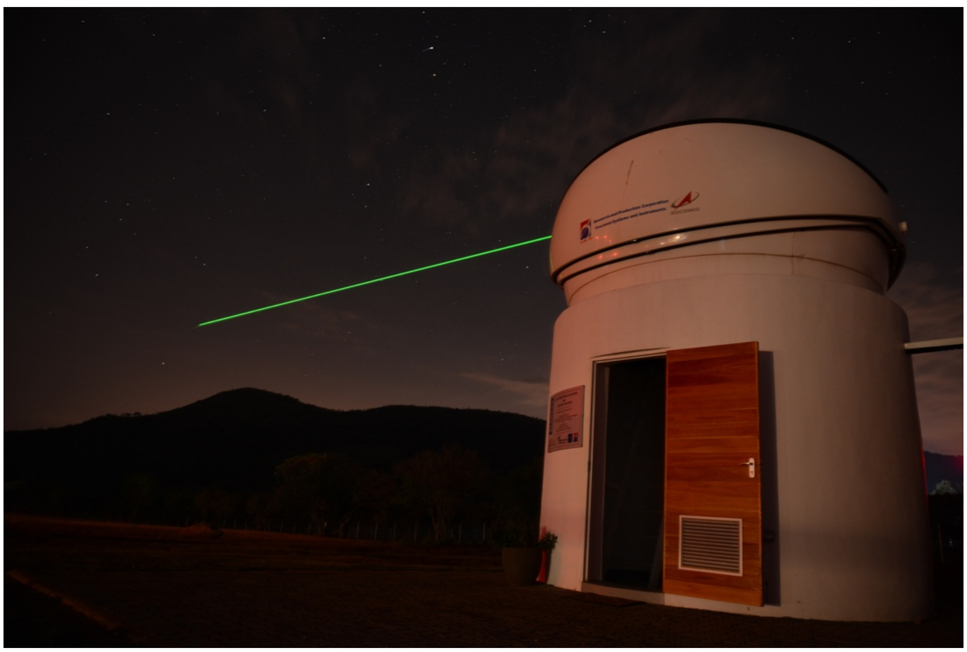

Figure 8-40: The Russian QOS "Sazhen-TM" in operation at the Hartebeesthoek facility of SARAO (photo credit: Jacoline Schoonees/DIRCO).

We endeavor to operate the station on a 24/7 basis, focusing as a first priority on targets of Russian interest (e.g., GLONASS) and then on the ILRS priority list.

System Improvements

Various system hardware issues were experienced from May through September 2018, negatively impacting the data yield. All problems were resolved by December 2018 and the station had a high level of functionality since that time. Regular software updates and improvements related to search, tracking and detection algorithms have been implemented.

Current Challenges and Future Plans

No serious technical challenges have been experienced and smaller issues are now usually resolved within a few days. We aim to have 24/7 operations until at least the end of 2020, without any major system or operational changes. Plans to improve the telescope dehumidification system by the end of 2019 are underway. The possibility of developing a new laser for QOS “Sazhen-TM” with a pulse duration of 45-60 ps (currently 300 ps) is currently under consideration.

Station Personnel

- Roelf Botha: Manager of the Sazhen-TM system and group
- Modibe Modiba: Sazhen-TM operator and team coordinator
- Caiphus Phale: Sazhen-TM operator
- Lionel Moralo: Sazhen-TM operator
- Adila Wamisho: Project PhD student and Sazhen-TM operator
- Vacant position: Sazhen-TM operator

Figure 8-41: The QOS “Sazhen-TM” team at Hartebeesthoek: (from left to right) Adila Wamisho, Caiphus Phale, Modibe Modiba and Lionel Moralo.

Contacts

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Krugersdorp — Website: *http://www.hartrao.ac.za*
SOUTH AFRICA

Herstmonceux, United Kingdom

Author: *Matthew Wilkinson, Robert Sherwood*
Responsible Agency: British Geological Survey

System: HERL/7840
Location: NERC Space Geodesy Facility, Herstmonceux, UK
Latitude: 50.8674° N, Longitude: 0.3361° E, Elevation: 75 m

Station Operations

The Space Geodesy Facility, Herstmonceux operates a prolific SLR system that is capable of supporting the full ILRS target list. The laser fires 1mJ, 10ps pulses at a rate of 1kHz, which are transferred to the emitter telescope through a coudé path of dielectric mirrors. The bi-static, azimuth-altitude, *Cassegrain, 50cm* telescope, tracks the target and directs the returning signal to a telescope-mounted SPAD detector. A narrowband filter is used to enable daytime observations and a variable neutral density filter is controlled to keep to low, single-photon levels of return rate. Two single-observer shifts are set every day, a day and a night duty, according to the satellite schedule. In-sky safety is ensured with an active radar, ADS-B tracking and the observer positioned alongside the telescope, all of which can inhibit the laser. The SGF also operates a number of GNSS receivers and absolute gravimeters.

Following a Strategic Review, NERC concluded that it shall continue to support the SGF and that it will be reclassified under the National Capability National Public Good funding stream from April 2018 and no longer be part of NERC's Services & Facilities portfolio. The SGF is now part of and managed by the British Geological Survey (BGS).

System Improvements

The performance of the kHz laser has been very good since the design upgrade in 2014, both in terms of energy output and reliability over time. This enabled routine high altitude GNSS satellite tracking in the day and fast inter-leaving between passes at night. Performance in the day was further boosted by the replacement of a daylight blocking filter in the receive path in 2015 and of the narrowband filter in 2018. However, the improvement from the new narrowband filter was not as great as expected and it is possible that the spectral laser line width is broader than this filter. The time required to produce a good normal point is significantly reduced with kHz, allowing for more frequent switching between satellite targets. An example plot showing this inter-leaving over two days is plotted right.

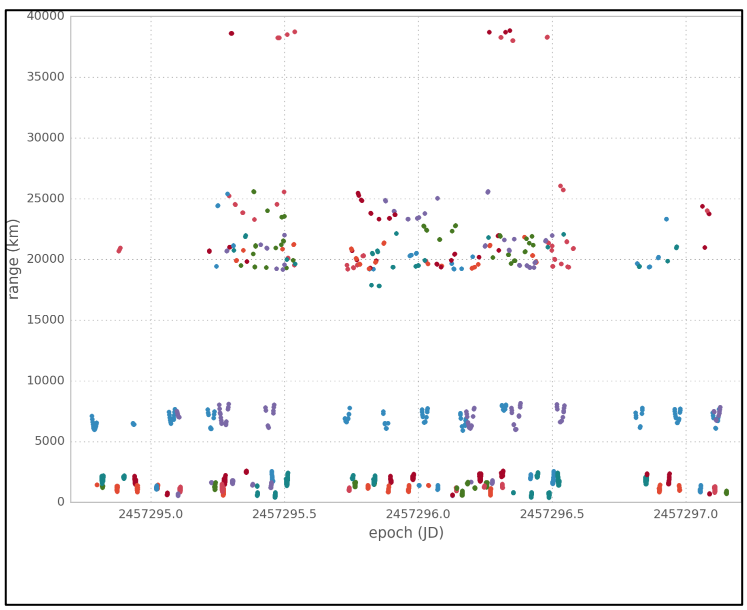

Figure 8-42. Pass interleaving using the kHz laser at Herstmonceux.

An A033-ET event timer from EvenTech was installed in 2014 to run in parallel with the HxET timer, which was constructed from two Thales Systems timing modules and a clock module. The new device is performing well and could become the future primary SLR timer. Using automatic, real-time track detection, the reduction method from this range data will be redeveloped for automation.

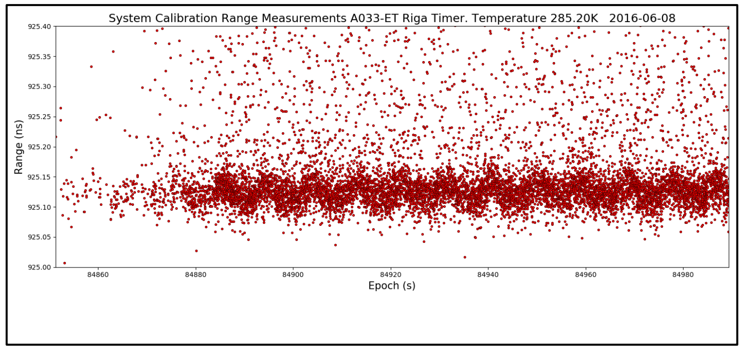

Figure 8-43. System calibration range measurements using A033-ET.

In 2016, a small, but visible, instability appeared in the laser range residuals, with an amplitude of approximately 1cm and a period of about 9 seconds, an example is plotted right. The source of this instability was found to be within the kHz laser itself. A service visit from the manufacturer was able to reduce this effect. The cause was later found to be a restricted flow of the cooling water through the laser bed, which required chemical cleaning.

In order to control the output polarization, a half-wave plate was placed outside the laser bed, which can be rotated using a stepper motor connected to a Raspberry Pi. By modelling the polarization orientation through the coudé path for all telescope positions, the linear polarized laser light can be fixed and switched by 90 degrees at the telescope emitter on command.

The SGF conducts regular height surveying using a Lecia DNA03 barcode level, with instrumental accuracy of 0.3mm. This is to assess the long-term stability of the SGF site and the stability of the inter-technique site ties. The results have shown good, sub-mm height stability and some variation at the ±1mm level in the monument for the HERS GNSS antenna. A site survey was carried out in 2017 to update the inter-technique site tie vectors between the telescope axis intersection invariant point and the reference markers on the SGF GNSS sites (HERS, HERT and HERO) and the absolute gravimeter floor studs. Included in the survey was the distance from the SLR telescope reference to the centre of retro-reflecting targets for terrestrial calibration of the SLR system delay. Agreement for this target was found at the polarization level with those from the previous survey carried out in 2008 by IGN. A newly constructed target pictured above right, with a well-defined reference point, was adopted as the primary SLR calibration target in 2018.

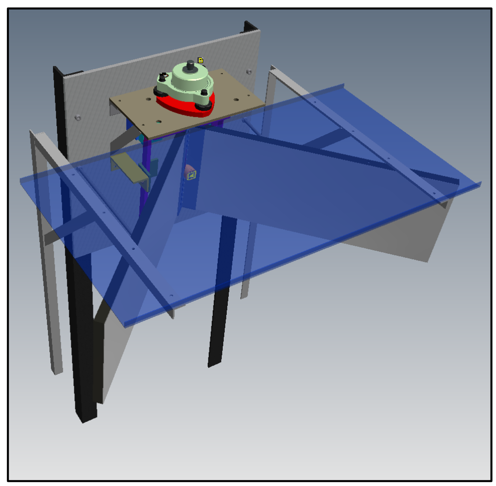

Figure 8-44. Diagram of new calibration target.

An active radar that tracks with the SLR telescope, an ADS-B receiver and the observer all switch off the laser beam should an aircraft approach the direction of fire. In addition to this, the advantages of an active camera system are being explored. Additionally, predictions for the International Space Station (ISS) were added to the ADS-B listen2planes TCP/IP server so that it will be treated like an aircraft and the laser will be inhibited if it approaches the beam.

A software program called orbitNP.py was released to the ILRS community in 2018, which originates from FORTRAN code used at the SGF that was translated into PYTHON. It reads full-rate data files, or raw epoch-range data, along with a corresponding CPF orbit prediction file to produce flattened range residuals by solving for time bias and range bias. The residuals are plotted for inspection and normal points are formed.

Future Plans

An assessment of what can be achieved with an optical camera aircraft detection system will continue as it is developed and tested. This will include day and night conditions as well as clear and partially cloudy skies. The advantages of colour images will also be explored.

Extraction of SLR returns from raw range data files recorded by the A033-ET Riga Event Timer are to be automated and this will be closely assessed for reliability.

The ability to control the polarization orientation at the telescope emitter will allow us to explore any impact on range measurements or return signal strength. This may lead to the installation of a quarter wave plate to produce circular polarization, which will be checked through the coudé path.

Station Personnel

Figure 8-45. SGF Herstmonceux team: Toby Shoobridge, Matthew Wilkinson, Dr. Graham Appleby, Victoria Smith, Robert Sherwood, Christopher Potter, José Rodríguez (left to right).

The SGF team is made up of seven personnel: Dr. Graham Appleby, Robert Sherwood, Christopher Potter, José Rodríguez, Toby Shoobridge, Victoria Smith, and Matthew Wilkinson. Six cover the observing schedule and within the team there is the required expertise in mechanical, software, electrical and optical engineering. Graham Appleby retired as head of the group in 2019, but will continue his involvement in the work of the SGF and its geodetic activities as a BGS Honorary Research Associate.

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Irkutsk, Russia

Author: *Valery A. Emelyanov*
Responsible Agency: East-Siberian Branch of FSUE "VNIIFTRI"

System: IRKL/1891
Location: 57 Borodina st., Irkutsk, 664056, Russia,
Latitude: 52.2191°N, Longitude: 104.3164°E, Elevation: 505.62m

Station Operations

The SLR station in Irkutsk (ILRS code IRKL, station number 1891) is one of the two laser stations in the ILRS network (along with MDVS), administered by the FSUE "VNIIFTRI" (Mendeleevo). The station is located on the outskirts of the Irkutsk city. The distance from Lake Baikal is 70 km, the distance from the reservoir on the Angara River is 500 m. The weather in Irkutsk can range from 10°C to 20°C (night)/20°C to 35°C (day) in the summer and -15°C to -35°C (night)/-5°C to -30°C (day) during the winter. There are typically up to 150 clear nights during the year.

Irkutsk station operates in both day and night and is capable of tracking all satellites on the ILRS priority list. The system can operate in a temperature range of -25°C to 30°C.

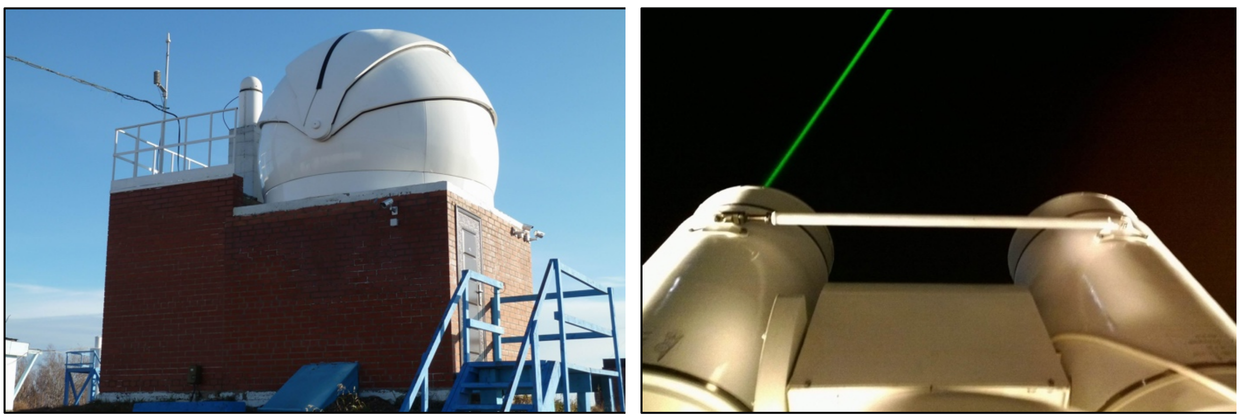

Figure 8-46. Daylight (left) and nighttime (right) observations at the Irkutsk laser station.

System Improvements

System characteristics:

- Name of the system: "Sazhen-TM"
- System manufacturer: OJC "RPC "PSI""
- Type of radiating- and TV-telescope: Gregorian
- Mirror aperture: 0.25 m
- Mount type: alt-azimuth
- Pulse repetition frequency: 300 Hz
- Pulse duration: 250 ps
- Laser type: ND: YAG
- Primary/secondary wavelength: 1064/532 nm
- Maximum output energy: 2.5 mJ
- Laser system resource: 10^9 pulses (~930 hours)

Established programs for laser observations are updated several times during the year.

Current Challenges and Future Plans

Every two years it is necessary to partially or completely replace the laser emitter due to the exhaustion of its resource.

Over the next year, the next generation of the "Tochka"-type laser station starting with sub-millimeter measurement accuracy is expected.

Station Personnel

Ten staff members are responsible for Mendeleevo station operations:

- Galina I. Modestova, head of department (station general management)
- Valery A. Emelyanov, responsible for the station operation (organizational, technical and software issues solution, observations)
- Victor V. Kaplenko, responsible for the station technical condition (technical issues solution, observations)
- Irina N. Bobrik, observer
- Andrey A. Chigvintsev, observer
- Elena P. Gladkevich, observer
- Pavel N. Modestov, observer
- Elena N. Myasnikova, observer
- Sergey I. Raschotin, observer
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Katzively and Simeiz, Crimea

Authors: *A.I. Dmytrotsa, I. Artemov, U. Martyshin, D. Neyachenko, A. Polyakov*
Responsible Agency: Crimean Astrophysical Observatory RAS (CrAO RAS)

System: KTZL/1893
Location: Katzively, Crimea
Latitude: 44.3932° N, Longitude: 33.9701° E, Elevation: 68.7 m

System: SIML/1873
Location: Simeiz, Crimea
Latitude: 44.4128° N, Longitude: 33.9931° E, Elevation: 361.20 m

Station Operations

The Simeiz station has been systematically operating since 1991. Currently, we observe low and high satellites at night.

Despite the fact that we have the oldest laser (operating since 1990), the station operates stably, and shows good results. Thanks to the enthusiasm and consistent modernization, the distance gradually increases the number of observations, without loss of accuracy.

As can be seen from the Global Report Cards from ILRS, the number of observations increases from year to year and approaches baseline, and the RMS has improved to about 12 mm.

Table 8-2. Summary of results for Simeiz from ILRS report cards (2016-2018).

	Passes				Normal Points				Minutes of	RMS		
Year	LEO	LAGEOS	High	Total	LEO	LAGEOS	High	Total	Data	Cal.	Star.	LAG.
2016	1324	230	89	1643	14922	1573	422	16917	12241		13.6	16.9
2017	1881	245	176	2302	21329	1582	846	23757	15174	25.9	11.0	11.6
2018	2313	286	377	2976	25369	1578	1605	28552	14672	20.8	12.0	13.6
2019	2018	234	273	2525	19841	1198	1200	22239	11124	17.3	11.8	16.2

By accessing the EUROLAS Data Center (EDC) service and making a selection of stations in the territory of the former USSR, you can see that the Simeiz station started from eighth place in 2016 and took first place in 2019, as shown in Tables 8-3 through 8-6).

Table 8-3. Pass totals from former USSR stations (2016).

N	Name	Total/Bad	LAGEOS	GNSS	LEO
1	1879-Altay	2754/0	271	2227	256
2	1868-Komsomolsk	2580/0	253	2169	158
3	1887-Baikanur	2162/0	450	1589	123
4	***1893-Katzively***	***2019/0***	***287***	***76***	***1656***
5	1890-Badary	1870/0	104	77	1689
6	1886-Arkhyz	1766/0	276	1013	477
7	1891-Irkutsk	1674/0	264	573	837
8	**1873-Simeiz**	**1666/1**	**235**	**91**	**1340**
9	1888-Svetloe	1514/0	240	108	1166
10	1889-Zelenchuk	1186/0	226	291	669
11	1884-Riga	1053/4	134	65	854
12	1824-Golosiiv	550/3	34	0	516
13	1874-Mendeleevo2	516/0	111	248	157

Table 8-4. Pass totals from former USSR stations (2017).

N	Name	Total/Bad	LAGEOS	GNSS	LEO
1	1879-Altay	3223/7	286	2653	284
2	1890-Badary	3017/12	172	147	2698
3	**1873-Simeiz**	**2354/4**	**253**	**184**	**1917**
4	1868-Komsomolsk	2341/1	157	2025	159
5	***1893-Katzively***	***2104/0***	***180***	***86***	***1838***
…	…	…	…	…	…
13	1888-Svetloe	256/0	8	15	233

Table 8-5. Pass totals from former USSR stations (2018).

N	Name	Total/Bad	LAGEOS	GNSS	LEO
1	**1873-Simeiz**	**3046/0**	**295**	**396**	**2355**
2	1891-Irkutsk	2744/1	334	849	1561
3	1879-Altay	2412/3	254	2019	139
4	***1893-Katzively***	***2262/3***	***210***	***9***	***2043***
5	1868-Komsomolsk	2215/0	210	1928	77
…	…	…	…	…	…
13	1874-Mendeleevo2	518/2	87	298	133

Table 8-6. Pass totals from former USSR stations (2019).

N	Name	Total/Bad	LAGEOS	GNSS	LEO
1	**1873-Simeiz**	**3169/27**	**322**	**413**	**2434**
2	1890-Badary	2928/313	520	499	1909
3	***1893-Katzively***	***2326/36***	***232***	***4***	***2090***
4	1879-Altay	2106/39	215	1772	119
5	1891-Irkutsk	2029/641	157	413	1459
…	…	…	…	…	…
13	1874-Mendeleevo2	280/32	72	132	76

As you can see, our station took first places in 2018 and 2019. Our second station, Katzively (1893), has been in the top five in 2016-2019 years.

System Improvements

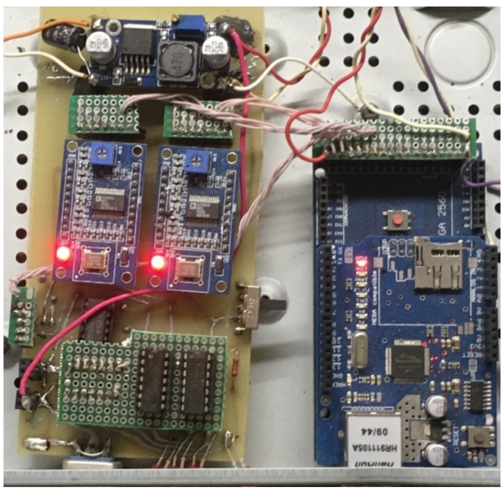

Figure 8-47. Replacement control board.

Despite these good results, the old laser does not make it possible to significantly increase the number of observations and normal points.

According to our plans, it is necessary to unload the control computer, update the equipment control boards and make them computer independent.

The main improvement over this period was the replacement of the engine control board (Figure 8-47). Previously, the board stood inside the computer, used the IDE protocol, now the control is implemented on the Arduino plate, and one controlled via Ethernet. The frequency for azimuth and altitude engines is generated by two frequency generators with an accuracy of 1Hz.

Current Challenges and Future Plans

On April 28, 2016, Moscow State University successfully launched the satellite "Lomonosov" from the new cosmodrome "Vostochnyi", located in the Far East Siberia, during the first launch. The main goal of this project is to study extreme processes in the space, such as Ultra High Energy Cosmic Rays, Transient Luminous Events, Gamma Ray Bursts, variations of the radiation environment, and to test the space segment of optical monitoring of potentially dangerous space objects.

In 2016-2017, our station participated in the ground support of the TUS instrument, on the Lomonosov satellite. To do this, it was necessary to create an ultraviolet laser, and to illuminate the satellite at the right time, for calibrating the TUS detector.

We also took part in the support of RadioAstron satellite. But from a distance more then 200,000 km, where sessions of laser ranging were usually conducted, we did not receive a reliable number of measurements.

To further improve our station, it is necessary to unload the control computer, update the equipment control boards and make them computer independent. Next in line is a time recording board and a board for working with angular encoders.

The second important part of the job is software improvement. Firstly, we need to upgrade programs to meet the new requirements in version 2 of both the CPF and CRD format standards. Secondly, with the change and addition of new equipment. To do this, we use client-server technology, where each item of equipment is managed in a separate service.

Summary

Despite the oldest laser, our station and, especially the team, show great potential. I hope that further modernization will allow us to occupy a worthy place among the laser ranging stations.

Our station took first places in 2018 and 2019. Our second station in Katzively (1893) has been in the top five in 2016-2019 years.

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Komsomolsk-na-Amure, Russia

Author: *Natalia Parkhomenko*
Responsible Agency: JC "RPC "PSI"

System: KOML/1868
Location: Komsomolsk-on-Amur, Khabarovsk Territory, Russia
Latitude: 50.69461°N, Longitude: 136.74383°E, Elevation: 269.4027m

Station Operations

The KOML 1868, a Russian Sazhen-C SLR, is located at the Solnechny district of the Khabarovsk Territory. The construction of the Sazhen-C station started during 1992. In the mid-1990s, the SLR station Komsomolsk-on-Amur began laser ranging sessions (ERS-1,2 and other) for the benefit of the satellite laser ranging community, which was organized in 1998 at ILRS.

The station staff strives to work on a 8/7 basis, focusing as a first priority on targets of Russian interest (e.g., GLONASS) and then on the ILRS priority list.

Figure 8-48. SLR system and facility located in Komsomolsk, Russia.

System Improvements

- Work was done to optimize algorithms and software related to the search and tracking of satellite, as well as the detection of a signal reflected from LRA on satellite.
- Developed and implemented a program for visualization/display of spacecraft flight paths.
- Modified the Diaphragm Switching Unit to increase the wear resistance of the field diaphragm positioning mechanism.

Current Challenges and Future Plans

Any problems with hardware and software are resolved quickly through remote consultations, and, if necessary, a specialist from PSI can visit the SLR station.

Future plans to improve the SLR system Komsomolsk-on-Amur:

- Development and implementation of digital cameras with a permeability of at least 12magnitude to replace the TV cameras that have outlived their life.
- Development and implementation of a laser with a pulse duration of not more than 60 ps.
- Development of software for calculating normal points directly at the station in order to reduce data access time for users.

Station Personnel

- Person 1: Manager of the Sazhen-C system
- Person 2: Sazhen-C operator
- Person 3: Sazhen-C operator

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Kunming, China

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Responsible Yunnan Observatory, CAS

System: KUNL/7820
Location: Kunming, Yunnan Province, China
Latitude: 25.0298°N, Longitude: 102.7977°E, Elevation: 1987.05m

Introduction

The Satellite Laser Ranging (SLR) station of the Yunnan Observatories lies in the eastern region of Kunming. The main observational facilities for laser ranging are the 1.2m telescope and the 53cm binocular. Currently, the 1.2m telescope is the primary experimental platform for Debris Laser Ranging (DLR) and Lunar Laser Ranging (LLR), while the 53cm binocular is designated for routine SLR missions. Both are operated by the Applied Astronomy Group (AAG) of Yunnan Observatories, Chinese Academy of Sciences.

Figure 8-49. The 1.2m Telescope and the 53cm Binocular.

In order to improve system performance and to satisfy the increasing needs for more ranging experiments, the observational systems were upgraded in 2016. The retrofit period lasted from August to the following January. Since then, routine SLR responsibilities were passed to the 53cm binocular.

With its routine SLR duty transferred, the 1.2m telescope can be fully devoted to DLR and LLR research. Equipped with new detectors, sampling devices and laser generators, the 1.2m telescope was capable of carrying out ranging experiments on space debris in 2016, and successfully received echo signals from the lunar retroreflector Apollo 15 in 2018, being the first system in China to achieve LLR.

The 53cm binocular is located about 30m distant from the 1.2m telescope; it has a separated optical-path structure. In 2017, SLR data from the 53cm binocular was uploaded to the EUROLAS Data Center (EDC), and passed the validation process later in November.

Overview of Satellite Laser Ranging Activities

Earlier, SLR was carried out intermittently at the 1.2m telescope, but most of the time was occupied by other research. Meanwhile, AAG members felt that the observational resources were too limited to perform so many ranging experiments, and started to deploy the new SLR system at the 53cm binocular. SLR data from the 1.2m telescope (station ID: 7820) was suspended in 2017, while the 53cm binocular was acknowledged later as "Station 7819" and its SLR data have been validated ever since.

The 53cm binocular transmits 532nm laser with 1kHz rate, each laser pulse is 25ps in width and 0.5mJ in energy. A single photon avalanche diode (SPAD) and A033-type event timer are applied.

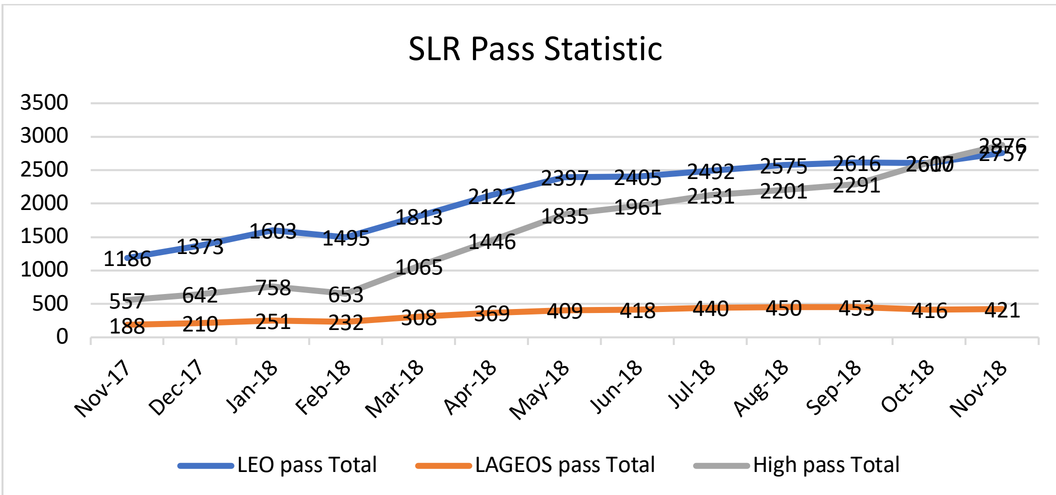

Figure 8-50. SLR passes statistics at Kunming.

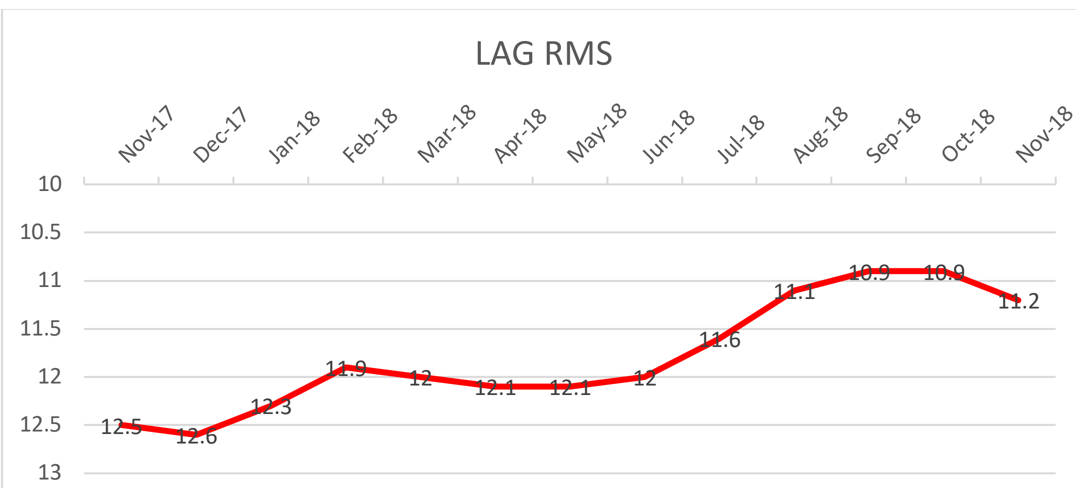

Figure 8-51. Average single-shot LAGEOS RMS (in millimeters).

As shown in Figure 8-50, the ranged pass by the binocular increased gradually, and the total pass number reached 6054 by 2018. Single-shot LAGEOS RMS values were more precise, from 12.5mm to 11.2mm, shown in Figure 8-51.

Overview of Debris Laser Ranging

DLR experiments were firstly carried out in the early 2010s, and new technologies such as a superconducting nano-wire single photon detector (SNSPD) high-speed event timer were gradually introduced into the ranging system since 2015.

A 1kHz 1064nm laser along with visible 532nm laser were transmitted from the 53cm binocular, while echo signals were received by both 1.2m telescope and 53cm binocular. A “Single-Transmitting and Dual-Receiving” ranging pattern was established for DLR research. The laser transmitting indicating signal was sent to the telescope side using fiber transferring technique. At the binocular’s receiving end, the detector was SPAD-type for 532nm laser echo and the event timer was A033-series, while the telescope-side used SNSPD array for 1064nm laser echo detection and GT668-type event timer for multi-channel sampling.

In early 2016, the system was capable of ranging meter-size debris at 837km. After the retrofit, during the experimental period from March to May in 2017, the system collected a total of 208 passes on debris targets. Calsphere 1 and 2 were detected during that time, which were about 1000km distant and their radar cross section (RCS) were at the $0.04m^2$-level.

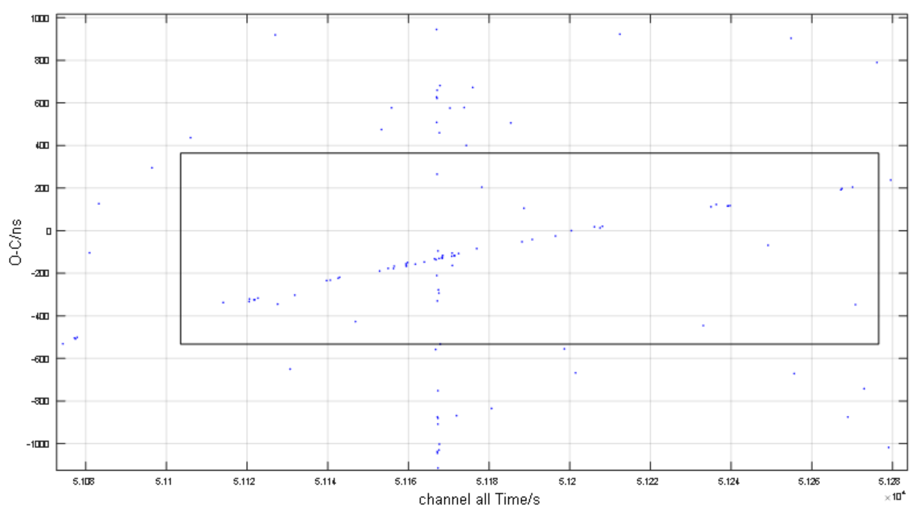

Figure 8-52. Echo signal of Calsphere 2.

Further improvements were introduced into the system in 2018, the software was upgraded. With 200W laser energy, the echo from the debris 12445 was detected, which had the range of about 6000km with its RCS of $18.25m^2$, shown in Figure 8-53.

Today, “the 53cm binocular transmitting and the 1.2m telescope receiving” pattern is mostly used in DLR experiments. Based on array detection and a multi-channel sampling technique, new data processing software was implemented. With further ranging technology research and the application of SNSPD, the system is now more precise and more efficient in DLR studies.

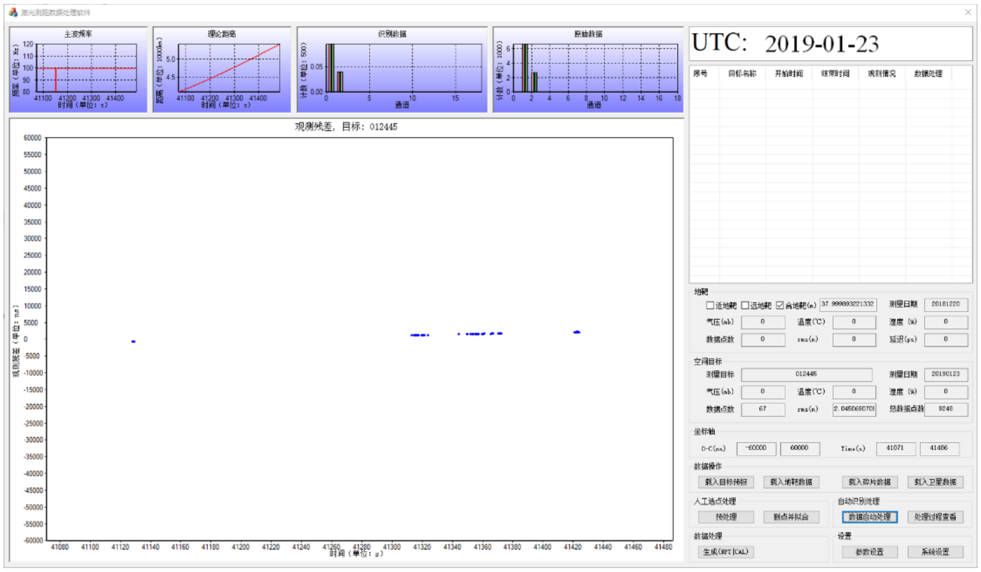

Figure 8-53. Echo signal of debris 12445.

Overview of Lunar Laser Ranging

The LLR system was established based on the retrofitted 1.2m telescope, in which common optical path was applied for high-precision pointing. 532nm laser (10ns pulse-width, 3.3J/pulse) of 10Hz rate were implemented, together with an exclusive range gate generator, high quantum-efficiency (HQE) SPAD and the A033 event timer, the system was finally prepared by November 2017.

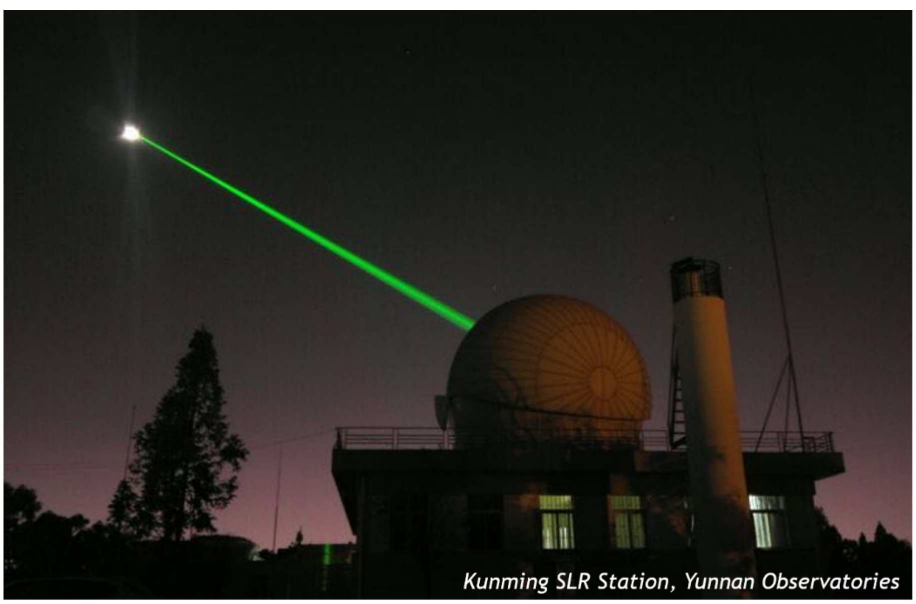

Figure 8-54. Pointing laser to the Moon.

On the night of Jan. 22, 2018, the first sign of echoes from Apollo 15 appeared. Computation and validation were carried out at once. Data were also uploaded to Lunar Laser Ranging Service developed by Paris Observatory Lunar Analysis Center for validation, and the results were exciting.

```
00056  2019/06/09  14h 08m 25s7525608   Apollo 15    Kunming          -0.064 m       -0.428 ns
00057  2019/06/09  14h 42m 54s0177808   Apollo 15    Kunming          -0.166 m       -1.106 ns
00058  2019/06/11  14h 46m 14s8770908   Apollo 15    Kunming           0.011 m        0.077 ns

Normal Points : 00058
Valid         : 00055
Wrong (***)   : 00003     Limit:      1.000 m

R0 Apollo 11  : 00004     Bias:     -0.004 m     -0.028 ns    St.dev.:      0.657 m      4.384 ns
R1 Lunokhod 1 : 00002     Bias:      0.390 m      2.599 ns    St.dev.:      0.190 m      1.268 ns
R2 Apollo 14  : 00006     Bias:     -0.151 m     -1.005 ns    St.dev.:      0.376 m      2.508 ns
R3 Apollo 15  : 00043     Bias:     -0.147 m     -0.982 ns    St.dev.:      0.363 m      2.420 ns
   Global     : 00055     Bias:     -0.118 m     -0.785 ns    St.dev.:      0.403 m      2.686 ns
```

Figure 8-55. Validation results.

The real-time data showed that the distance between the Apollo-15 retroreflector and Kunming station was 385823.433km to 387119.600km, during 21:25 to 22:31, Jan. 22, 2018. In the following days, echoes from Apollo-15, Apollo-14, and Apollo-11 were detected one after another, totally 35 passes with general accuracy better than 1m.

Summary

In recent years, the Kunming station has made great effort in developing SLR technologies and has achieved considerable progress. In 2016, the primary SLR duty was transferred from the 1.2m telescope to the 53cm binocular. After the retrofit, the telescope has been mainly used for DLR and LLR research, while the binocular is serving routine SLR activities. The LLR system was developed in 2017 and in the next year LLR achieved ranging success. As of today, the station keeps improving its research in related technologies for future laser ranging development.

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Matera, Italy

Author: *Giuseppe Bianco (ASI), Daniele Dequal (ASI), Giuseppe Nicoletti (e-GEOS)*
Responsible Agency: Italian Space Agency (ASI)

System: MATM/7941

Latitude: 40.6486°N, Longitude: 16.7046°E, Elevation: 536.9m

Station Operations

The Matera Laser Ranging Observatory (MLRO) is operational since 2000 and has been conceived to be a multipurpose state-of-the-art observatory capable of supporting a variety of experiments. Equipped with a 1.5 meter telescope, its main mission is the laser ranging to artificial satellites and Moon but is more and more involved in quantum communication experiments.

Figure 8-56. MLRO system in operation.

During the years 2016-2019 the MLRO station has been in routine, full time (24/7) operations, with the exception of two months in 2016 (June-July) and two months in 2019 (June-July) for the primary mirror recoating. The Figure 8-57 below represents the weekly number of passes observed by MLRO in the four years of this report.

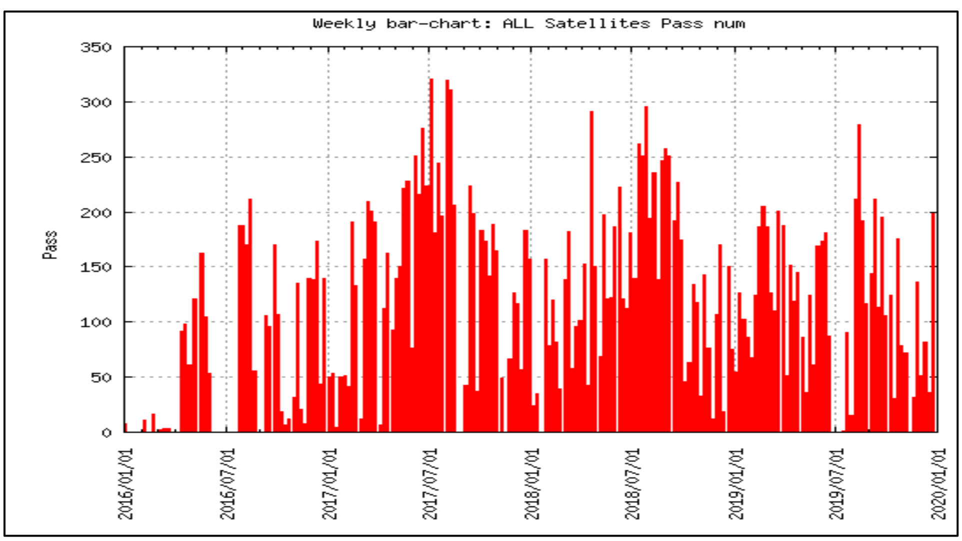

Figure 8-57. The monthly number of passes observed by MLRO in the past three years.

A small amount of data was acquired at the beginning of 2016 due to a failure of the telescope controller.

The average single-shot LAGEOS RMS, in millimeters, during the last quarter of 2019, is plotted in the following graph (Figure 8-58) as reported in the ILRS Global Performance Report Card.

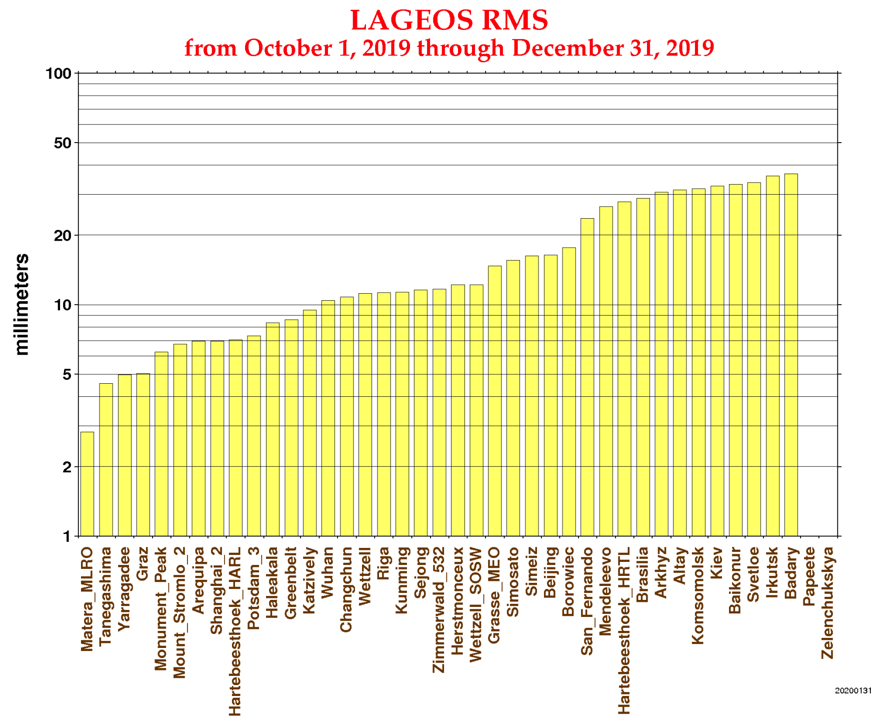

Figure 8-58. The LAGEOS RMS values for MLRO during 2019.

The acquisition of lunar data was improved with the replacement of the photomultiplier. The new Hamamatsu proved to be more efficient and the number of lunar observations per normal point is continuously increasing, as reported in the Figure 8-59. The tracking is performed during the first and last moon quarter for a couple of hours each night.

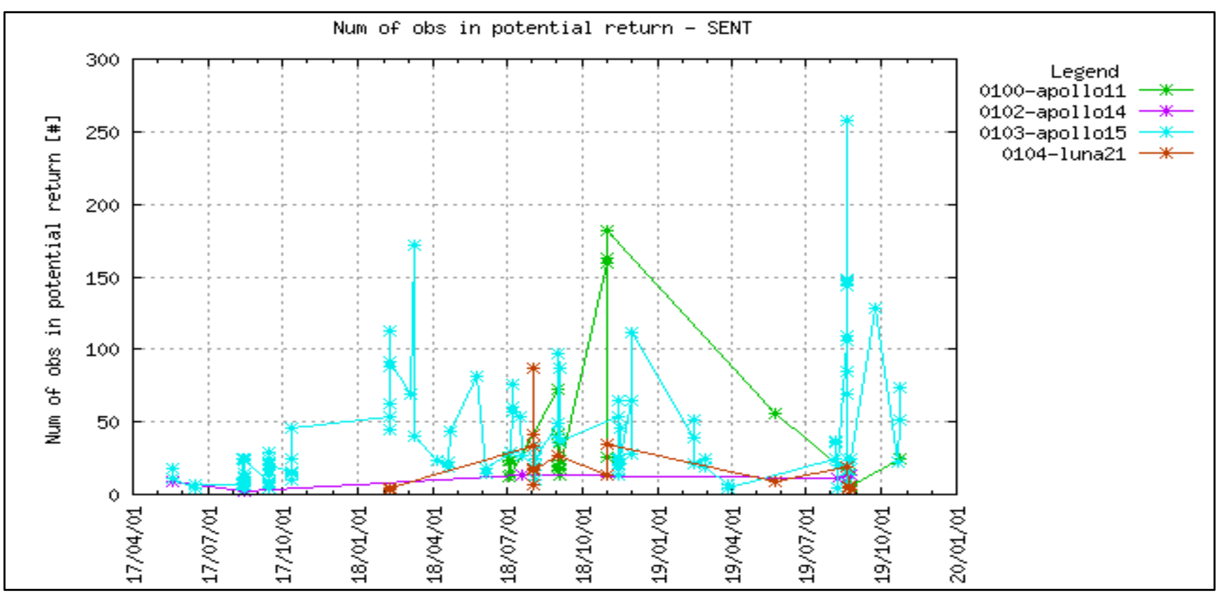

Figure 8-59. MLRO LLR observations (2017-2019).

System Improvements

- 2016: an upgraded state of the art servo-control system replaced the original Contraves Telescope control system, the installation was completed by Cybioms Corporation March 2016.
- 2016: MLRO is based on a 1.5-meter diameter Cassegrain telescope which was built in 1995. The primary mirror had a UV-enhanced coating with a very high reflectivity; however, after 20 years, it had degraded significantly and a new coating had become necessary. The recoating was completed in July2016.
- 2017: in December 2017 the Photek PMT was replaced with an Hamamatsu PMT.
- 2018 -2019 : Coudé path mirrors replacement from M7 to M2.
- 2019 : In June primary mirror re-coating due coating degradation.

Current Challenges and Future Plans

MLRO has been used for more than a decade to perform studies in the field of satellite quantum communication. The activities done so far exploited passive satellite equipped with retroreflector. In order to realize a high efficiency quantum-key-distribution (QKD) ground station, MLRO is undergoing an upgrade of telescope mirrors as well as detection apparatus. The station is now ready to receive quantum signals from the Chinese satellite Micius, and further upgrades will make it the reference national ground station for the in orbit validation of a QKD payload, founded by ASI. Upgrades will include new mirrors coating, an adaptive optics system and superconducting nanowires detectors.

MLRO is considered a national asset to be used for Space Surveillance and Tracking. Preliminary test demonstrated the capability of MLRO to track debris equipped with retro-reflectors, such as the rocket body CZ-2C R/B, However, its involvement in ILRS experiment and ESA projects stated that the system is not currently qualified to track uncooperative targets. The system low repetition rate (10Hz) revealed to be a big gap and the MLRO will undergo an upgrade.

MLRO will be improved with the update of the HW platform and the installation of the SW on the new platform, in order to preserve the current functionalities and support new features. Obsolete parts will be replaced with COTS subsystem, whenever possible.

Station Personnel

The Italian Space Agency is the owner of the Observatory and is the decision making body. The operations are performed by e-GEOS S.p.A. (formerly Telespazio) since the very beginning in the 80’s. A shift of ten people is running all the geodetic operations at the Space geodesy Center (SLR/LLR, VLBI, GNSS, gravimeter). The SLR/LLR operations and maintenance are coordinated by the SLR operation manager and a team of engineers is supporting preventive and corrective maintenance.

Contacts

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McDonald TX, USA

Authors: *Peter J. Shelus, Randall R. Ricklefs, Jerry R. Wiant, John C. Ries*
Responsible Agency: Center for Space Research (CSR), University of Texas at Austin

System: MDOL/7080
Location: McDonald Observatory, near Fort Davis, TX
Latitude: 30.6802° N, Longitude: 255.9848° E, Elevation: 2006.2210m

Station Operations

For the period in question (2016-2019), the McDonald Laser Ranging Station (MLRS) has been virtually non-operational (see below).

Figure 8-60. McDonald Laser Ranging Station (MLRS).

System Improvements

From the mid-1980's through the first decade of the 21st century, the MLRS provided more than 25 years of nearly flawless operation. During most of that time, the MLRS was one of the few laser ranging stations in the world that routinely ranged to the Moon and was one of the better, steady data producers. Sadly, for the past 10 years or so, the MLRS has been in a spiraling decline, principally due to a steadily deteriorating MCP/PMT. Because of budgetary reasons, the MLRS had not been a participant in the general NASA network-wide MCP/MPT upgrade that occurred about 5 years ago. The decline was exacerbated by the retirement of the sole, remaining laser technician, on August 31, 2015. This left MLRS with only a single observer and no skilled laser technician. Unfortunately, a laser upgrade in the summer of 2015 did not ameliorate the steady loss of sensitivity of the MCP/PMT.

In the spring of 2019, the MLRS received a replacement MCP/PMT. Working with T. Oldham and other NASA personnel, Wiant and Ricklefs worked to bring the MLRS back to its former operating condition. Regrettably, before much progress could be made, a severe lightning strike occurred on September 12, 2019 that seriously affected many of the instruments at the Observatory and dealt a fatal blow to the MLRS system. With the upcoming installation of SGSLR at McDonald, NASA decided to abandon any further attempts to resurrect MLRS; and the system was subsequently shut down permanently.

Figure 8-61. MGO VLBI antenna.

Figure 8-62. MGO gravimeter hut.

Current Challenges and Future Plans

As a part of the present NASA contract, a "new" McDonald Geodetic Observatory (MGO) is under construction. Combining artificial satellite laser ranging (SLR), very long baseline interferometry (VLBI), and the Global Navigation Satellite System (GNSS), plus associated local position monitoring at a single installation, the MGO will join other similar geodetic observatories around the world in facilitating the study of the Earth's shape, gravity and rotation.

Supplementing NASA's equipment investment, the University of Texas at Austin has contributed a GWR superconducting gravimeter (SG) as a permanent part of MGO. This makes MGO similar to most multi-technique geodetic observatories in Europe and elsewhere, which also operate an SG in addition to SLR, VLBI and GNSS equipment. The SG hut is now in place on the 'guest pad' on Mt. Fowlkes, and the SG was moved there in late September 2019. The VLBI passed its Site Acceptance Test in February 2019; and a piezometer was installed in October 2019 to measure groundwater pressure/flow near the gravimeter hut.

Burke Fort, John Ries, Randall Ricklefs, Peter Shelus (left to right)

Figure 8-63. MLRS station personnel.

Station Personnel

During 2016-2019, the following personnel have supported activities at MGO:

- Peter J. Shelus – MGO Principal Investigator (now retired)
- Srinivas V. Bettadpur – Original MGO Co-Principal Investigator
- Burke O. Fort – MGO Project Manager (now Co-Principal Investigator)
- Jerry R. Wiant – Station Engineer (now retired)
- Eusebio "Chevo" Terrazas – VLBI Operations Support Technician (OST)
- Randall R. Ricklefs – Software Engineer
- John C. Ries – SLR Data Quality Control (now Co-Principal Investigator)
- Anthony Garcia – Observer (no longer at MGO)

Rachel Green – Technical Staff Assistant (no longer at MGO)Contact

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Websites: *https://space-geodesy.nasa.gov/NSGN/sites/MGO/MGO.html*
https://mcdonaldobservatory.org/news/releases/20180820

Mendeleevo, Russia

Author: *Igor Yu. Ignatenko*
Responsible Agency: FSUE “VNIIFTRI”

System: MDVS/1874
Location: Mendeleevo, Solnechnogorsk District , Moscow region, 141570, Russia,
Latitude: 56.027736 °N, Longitude: 37.224903 °E, Elevation: 229.053 m

Station Operations

The Mendeleevo station (ILRS code MDVS, station number 1874) is one of the two ILRS network laser stations (along with Irkutsk/IRKL), administered by the FSUE “VNIIFTRI”. Federal State Unitary Enterprise (FSUE) “National Research Institute for Physical-Technical and Radio Engineering Measurements” (VNIIFTRI) is subordinated to Federal Agency on technical regulation and metrology of Russia, has the status of the State scientific metrological center and is one of the main Centers of the State standards of Russia. At present, VNIIFTRI supports and improves 38 State standards, 19 secondary standards, 23 rigs of highest accuracy, over 120 working standards and calibration rigs for various fields of measurement. VNIIFTRI performs the duties of the Main metrological center of the State service of time, frequency and the Earth rotation parameters determination (SSTF). The institute has been engaged of satellites laser ranging since the 70s of the last century. The third generation of equipment is currently in operations at the Mendeleevo station; the system is capable of both day and nighttime tracking all satellites on the ILRS priority list. The system can operate in a temperature range of -25°C to 30°C.

The station is located on the outskirts of the Moscow city. The weather in Mendeleevo can range from 10°C to 20°C (night)/20°C to 35°C (day) in the summer and -5°C to -35°C (night)/-5°C to -30°C (day) during the winter. There are typically up to 150 clear nights during the year.

Figure 64. Daylight (left) and nighttime (right) observations at the Mendeleevo laser station.

System characteristics:

- System name: “Sazhen-TM”
- System manufacturer: OJC “RPC “PSI”“
- Type of radiating- and TV-telescope: Gregorian
- Mirror aperture: 0.25 m
- Mount type: alt-azimuth
- Pulse repetition frequency: 300 Hz

- Pulse duration: 250 ps
- Laser type: ND: YAG
- Primary/secondary wavelength: 1064/532 nm
- Maximum output energy: 2.5 mJ
- Laser system resource: 10^9 pulses (~930 hours)

Established programs for laser observations are updated several times during the year.

System Improvements

New technical solutions, measurement and calibration techniques are being implemented at the Mendeleevo station; these modifications are also being implemented at other existing stations of the network. Some of these decisions have become part of the next-generation station.

Current Challenges and Future Plans

Every two years it is necessary to partially or completely replace the laser emitter due to the exhaustion of its resource.

Over the next year, the next generation of the "Tochka"-type laser station starting with sub-millimeter measurement accuracy is expected.

Station Personnel

Ten staff members are responsible for Mendeleevo station operations, including:

- Sergey L. Pasynok, head of EOP department of VNIIFTRI
- Igor Yu. Ignatenko, head of laser ranging service of FSUE "VNIIFTRI," scientific and methodological guidance, responsible for the station operation (organizational, technical and software issues solution, observations)
- Efim N. Tsyba, scientific researcher of VNIIFTRI, development of the SLR and LLR processing software, development of the methods of parameter estimation
- Vacheslav S. Ivanov, responsible for the station technical condition (technical issues solution, observations)
- Vasiliy R. Schlegel, scientific researcher of VNIIFTRI, technical and software issues solution, observations
- Aleksey E. Drozdov, student of the Physics Faculty of Moscow State University, our concern for the future, observations.

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Monument Peak CA, USA

Author: *Ron Sebeny*
Responsible Agency: NASA GSFC

System: MONL/7110
Location: Monument Peak
Latitude: 32.8917° N, Longitude: 116.4227° W, Elevation: 1842.177 m

Station Operations

The MOBLAS-4 system, located at Monument Peak, CA, operates 16 hours per day (06:00 a.m. to 10:00 p.m. local time), five days per week. The station is operational for all scheduled satellites.

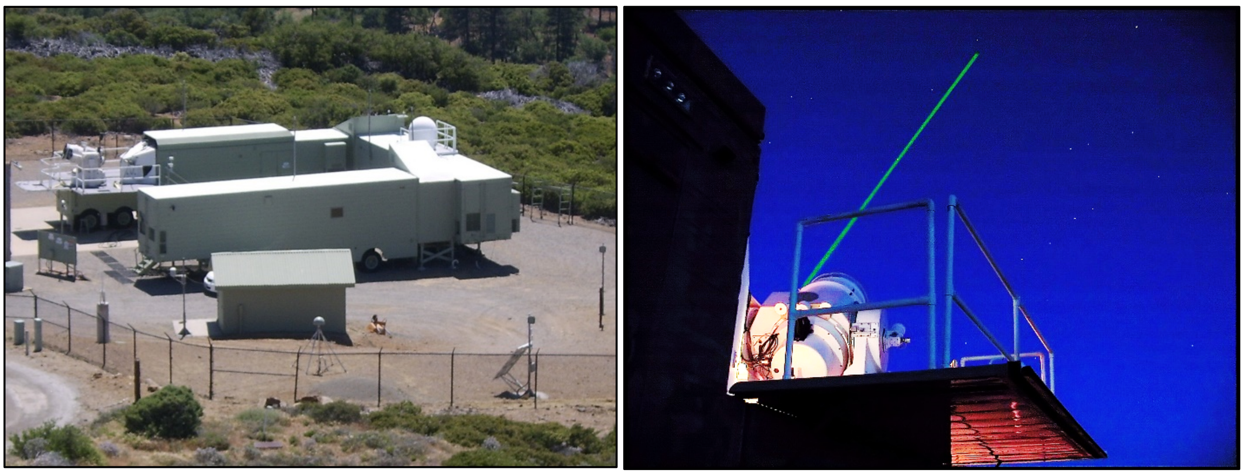

Figure 8-65. NASA SLR station located in Monument Peak, CA.

System Improvements

- The Geostationary Lightning Mapper (GLM) equipment was installed at Monument Peak on June 17, 2017 in support of NASA's participation in a GOES-R experiment. Tracking with the GLM started on September 17, 2018.
- In 2019, the Event Timer Module (ETM) officially replaced the TIU as the primary data measurement system after test data were reviewed and approved by the ILRS Analysis Standing Committee (ASC).
- Completed harmonic drive modification/upgrade in the radar as part of a Laser Hazard Reduction System (LHRS) improvement. Additional processes and procedures were put in place to ensure the radar is always aligned with the telescope.

Current Challenges and Future Plans

- The station plans to continue tracking all satellites for the ILRS and GLM projects.
- Sustainment of obsolete parts and equipment is becoming more difficult, however sustaining engineering is taking on multiple efforts to procure, test, and evaluate replacement solutions.
  - Low signal loss and more durable PMT cables.
  - Stanford Research Systems FS740 to replace the XL-DC.
  - Laser Power Supply and Start Diode replacements.
  - Improvement of heating, air, and ventilation system.
  - Procurement of spare tachometer generator and brush-rings.

Station Personnel

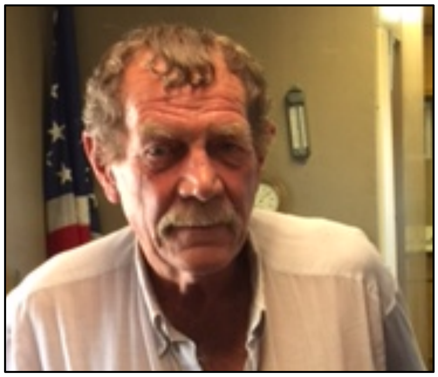

Figure-8 66. MOBLAS 4 Ted Doroski and Ron Sebeny.

The crew members track over fifty satellites during operational shifts. In addition, they perform preventive and regular maintenance of the station during the work week. The station staff members are:

- Ted Doroski: Engineering Technician, Operator
- Ron Sebeny: Station Manager, Operations & Engineering Support Team
- Ken Tribble, Engineering Technician/Operator
- Dennis Chase, Lead Engineer
- Jason Laing, Data Operations Lead
- Christopher Szwec, SLR Project Manager

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Mount Stromlo, Australia

Author: *Chris Moore, Nick Brown*
Responsible Agency: Geoscience Australia

System: STL3/7825
Location: Mount Stromlo, Canberra, ACT, Australia.
Latitude: 35.3161° S, Longitude: 149.0099° E, Elevation: 805.0 m

Station Operations

The Mt. Stromlo Space Research Centre is a fundamental space geodesy site that currently consists of a high precision satellite laser ranging (SLR) station based on a 1m aperture telescope, and an experimental facility based on a 1.8m aperture telescope. The site is also supported by IGS GPS and IGLOS GLONASS receivers, IDS DORIS beacon, and a comprehensive local tie network.

SLR

Since November 2015, the Mt. Stromlo SLR station has been operated by EOS Space Systems Pty Ltd under contract to Geoscience Australia.

The station has operated continuously throughout this period and remains one of the most productive stations in the ILRS network. Figure 8-67 shows the productivity that has been achieved during 2016-18 in terms of number of passes of low earth orbit (LEO), high earth orbit (HEO/GEO) and LAGEOS satellites.

Routine 24/7 operations were performed autonomously and often unmanned. The sealed telescope enclosure, shown in the Figure 8-68 is one of the aspects of the station that allows such a high level of automation.

GNSS

The two IGS sites at Mt. Stromlo (STR1 and STR2) continue to provide a variety of GNSS data products, including a 1 Hz real-time data stream. A third GNSS antenna/receiver installed at the observatory on the northwest pillar is capable of tracking the Galileo satellites along with GPS and GLONASS, and is providing a 1 Hz real-time stream to the Cooperative Network for GIOVE Observation (CONGO) project.

Since Q1 2016, the Mt. Stromlo station incorporates a new monitoring station to support tracking of the Chinese Beidou satellite constellation.

Local Tie Survey

A full local tie survey was completed in September 2018 including the connection to the new GPS mount. A report detailing the survey is in preparation.

Gravimetry

As part of the AuScope gravity program the Reynolds dome at Mt. Stromlo was refurbished into a dedicated absolute gravity comparison facility for four instruments. The super-conducting gravimeter continues to operate, with frequent calibration from AuScope's FG5 237 gravimeter. Continuing observations from this gravimeter extend the vertical gravity monitoring series at Mt. Stromlo.

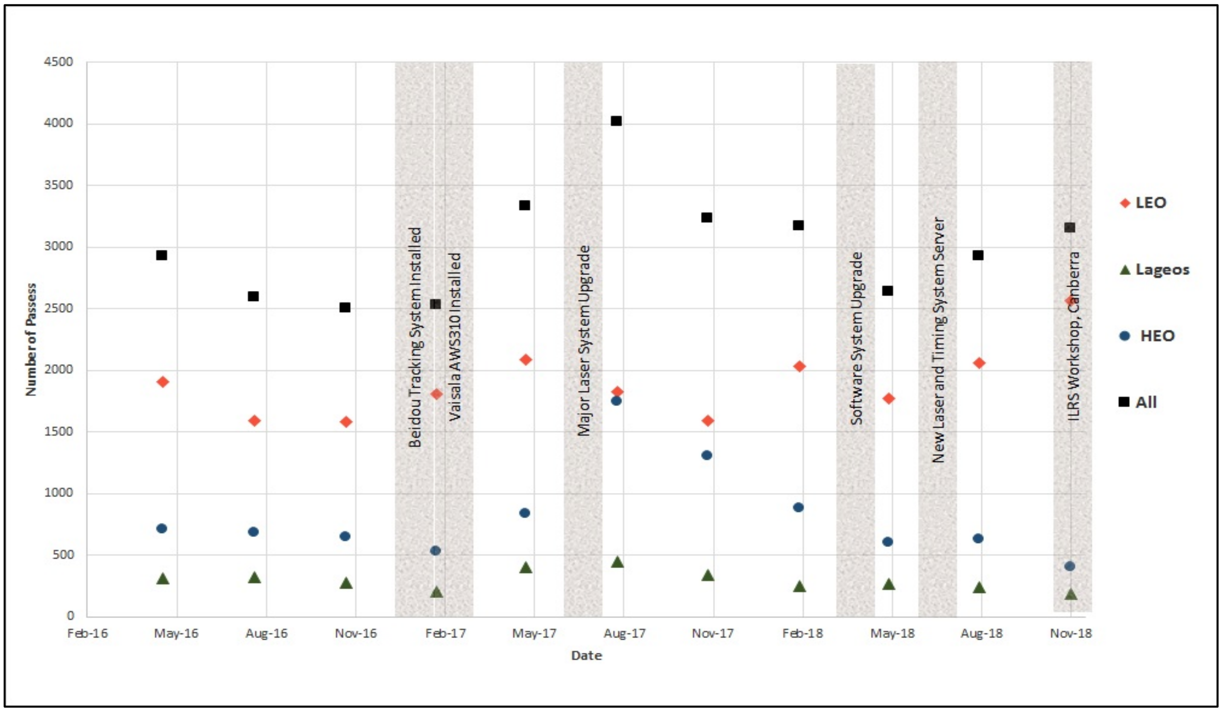

Figure 8-67. Productivity at Mt. Stromlo during 2016-2018, identifying major events.

Station Personnel

Staffing levels during 2016-2018 has typically required attendance of one person during normal business hours and occasional remote monitoring at other times. These duties were shared between Dr Christopher Moore (station manager) and operational support provided by Mr. Jonathan Poonpol and more recently by Mr. Babak Soltanfar. Given that EOS Space Systems provides SLR services under contract from Geoscience Australia, Mr. Mark Blundell also provides contract management services.

Figure 8-68. Mt. Stromlo SRC and EOS Space Systems staff, Mark Blundell (left) and Christopher Moore (right).

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Potsdam, Germany

Author: *Sven Bauer*
Responsible Agency: GFZ Potsdam

System: POT3/7841
Location: Potsdam, Brandenburg, Germany
Latitude: 52.3830° N, Longitude: 13.0614° E, Elevation: 123.5 m

Station Operations

Daytime and nighttime operation whenever there is good weather and actually somebody available for observations. However, retiring staff is continuously reducing the personnel, which reduces the station performance.

Figure 8-69. Potsdam laser installation (photo credit S. Bauer).

System Improvements

- HighQ laser system upgrade which increased the pulse energy and reduced the pulse length,
- Finally, successfully integration of an MPD SPAD in the system which reduced the measurement RMS (down to 2.5 mm one-way e.g., for Swarm), increased the signal return rate (GLONASS e.g., 1000 echos in 10 min before, now 10000 echos) and stabilized the station system delay due to less variation and sensitivity to external effects,
- Software updates improving station operation towards automation, in-sky and laser safety as well as hardware and system control,
- Establishment of the time bias service for analysis and comparison of prediction providers and quality as well as prediction of time bias values for various targets for the ILRS community.

Current Challenges and Future Plans

- Fully automated station operation during nighttime.

Station Personnel

- Sven Bauer/GFZ: Station manager
- Jens Steinborn/Digos Potsdam GmbH: IT and station operation and system software development (contracted)
- Andre Kloth/Digos Potsdam GmbH: IT and station operation and system software development (contracted)
- Stefan Weisheit/GFZ: Electronics and observer
- Martin König/GFZ: Electronics and observer
- Marcel Ludwig/GFZ: Mechanics and observer
- Students (one to two): Observer

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Riga, Latvia

Author: *Kalvis Salmins, Jorge del Pino*
Responsible Agency: Institute of Astronomy, University of Latvia

System: RIGL/1884
Location: Riga, Latvia
Latitude: 56.948551° N, Longitude: 24.059075° E, Elevation: 31.3367 m

Station Operations

The Riga SLR station (1884, RIGL) is situated at the University Botanical Garden in Riga, Latvia and now operates during night and twilight, seven days a week. The number of clear nights is on average 120 nights per year with a low season during October through January. The system tracks all the satellites up to the GLONASS/Galileo orbits. Due to the event timer RTS 2006 software design, range is currently limited to 25,500 km.

After two quarantine periods (data released on 2016-04-16 and 2017-02-01) the station was validated and operational since 2017-02-01. Segmented tracking, fast switching between satellites, and simultaneous TerraSAR-X/TanDEM-X tracking are now implemented and used on a regular basis, improving the station productivity.

Figure 8-70. Riga station view: The SLR system, GNSS antenna, new local network markers (lower right, top right and near the GNSS antenna) and groundwater monitoring well (yellow circle). Between the SLR and the lower right marker is the old AFU-75 satellite photo camera shed.

The total number of passes and normal points for the 2016-2019 period are: LAGEOS/LARES 748/7547, HEO 225/1165, LEO 3013/47955 and non-ILRS targets (TOPEX/Poseidon, ADEOS-2, Oicets) 276/4960.

The total observing nights where: 119 (2016), 100 (2017), 123 (2018) and 94 (2019).

Two hardware breakdowns occurred during 2017 (and documented in SLRMail messages 2455 and 2456) and affected the system operation, reducing the tracking output. Notable results during the 2016-2019 reporting period are as follows. Riga was the first station to observe an SNET satellite (SNET-4 on 2018/04/12 at 21:57 UTC) and the second station to report passes of GRACE-FO-1 and -2 after Potsdam (2018/05/24 at 21:54 UTC). In October 2017, The Riga staff hosted the 2017 ILRS Technical Workshop “Improving ILRS Performance to Meet Future GGOS Requirements”.

The SLR station is co-located with the IGS GNSS station RIGA00LVA as well with a gravimetric site with regular relative gravity and groundwater level measurements complemented by a visiting absolute gravimeter.

System Improvements

A full description of the system improvements for 2016-2019 can be found in the posters presented at the two International Workshops on Laser Ranging (Potsdam 2016, “SLR Station Riga Status Report” and Canberra 2018, “SLR Station Riga Status Report 2018”) as well as other posters or presentations during the same period.

SLR telescope building:

- External building walls and rolling roof pillars repaired.
- New utility power lines, UPS system and security light system.
- A new temperature control system in the laser room.

SLR system hardware:

- Primary and secondary telescope mirrors replaced and full optical system alignment.
- The telescope power and data cables replaced in 2017.
- The new Hamamatsu APD module C5658 (start channel) and a Hamamatsu H11901-20 PMT + Hamamatsu C5594 Amplifier (stop channel) installed.
- The new fiber optics internal calibration system installed and calibrated.
- A new narrow field camera Andor iXon Ultra 888 was installed in December 2019.
- Four cameras in operation: All-Sky, wide field and narrow field for visual tracking, and IR webcam to monitor the telescope movement.
- A Calibration/Tracking configuration switch, doubling as the laser beam emergency blocker.
- A remote controlled PMT filter selection with 3 IF + 2 ND.
- The TS/ATIC (Time Selector/Amplitude to Time Interval Converter), for improved signal processing electronics is operational since the last quarter of 2019.
- The Sky clarity sensor Aurora Cloud Sensor III with rain and snow alarm.
- A new backup meteorological station Vaisala PTU300. The pressure sensors on the primary WXT510 and PTU300 stations were recalibrated against the Potsdam SLR absolute barometer.
- The height difference between the meteorological station Vaisala WXT510 and the SLR and GPS reference points was remeasured.
- Three new local network reference points.
- A Raspberry PI-based temperature monitoring system at the laser and control rooms.
- All station software, except the DOS legacy programs controlling the telescope, has been ported to run under Windows 10.
- Since January 1st, 2018, the sky clarity is permanently monitored in cooperation with the Metsähovi SLR team in order to evaluate the long term local and simultaneous cloudiness statistics. (see the Stuttgart 2019 poster “Continuous Sky Clarity Monitoring at Riga and Metsähovi: January 2018 - June 2019”).

In development:

- The computer-controlled beam divergence unit.
- The upgraded detector enclosure for optical, thermal and EMI protection of the detector.

Current Challenges and Future Plans

Current challenges:

- To increase daylight tracking time
- Event timer software upgrade

Near future plans are:

- Build a new detector unit
- New telescope control system
- New event timer
- Better thermal insulation for telescope and equipment compartments

Station Personnel

- Kalvis Salmins: Station manager, researcher
- Jorge del Pino: Researcher
- Janis Kaulins: Researcher, joined late 2018
- Aivis Meijers: SLR operator, technician
- Janis Sarkovskis: SLR operator
- Igors Abakumovs: SLR operator

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San Fernando, Spain

Author: *Manuel Catalán*
Responsible Agency: Real Instituto y Observatorio de la Armada

System: SFEL/7823
Location: Spain
Latitude: 36.4650° N, Longitude: 6.2055° W, Elevation: 98.177 m

Figure 8-71. San Fernando SLR station during laser operations.

Station Operations

Station tracking statistics from 2016 to 2019 are shown in Table 8-7 below. During 2016, the programmed observations of the daily routine of tracking artificial satellites continued. We included in our routine inactive satellites (collaborative objects) as was proposed as a goal in the Research Project entitled "Contribution of the Laser Station for monitoring of artificial satellites of the ROA.

Table 8-7 reflects the performance of the system throughout every year (2016-2019). It includes both active satellites with retroreflectors, and inactive collaborative objects.

Normal operations were performed from January to June 2017. Our tracking efficiency was low in 2018 as we were mainly involved in technical achievements. In 2018 from March 22th to April 1st, we participated in a campaign especially devoted to the reentry of the Chinese space station Tiangong-1.

Return echoes were first achieved on January 16, 2019 with the EKSPLA PL2251 PS laser. Between February 17 and March 20, 2019, we participated in SST survey campaign corresponding to the 20/2017 NEG Archive (DPEERT/DERT) in collaboration with CDTI and the European Union.

In early June 2019 we worked with the ILRS Analysis Standing Committee to re-join the ILRS network. From then until the end of December our data were under quarantine, performing an intensive campaign specially focused on the LAGEOS-1, LAGEOS-2, and LARES satellites. On November 27, 2019 we were informed that the station passed the evaluation phase, and that it was accepted again as member of the ILRS network.

Table 8-7. Tracking statistics for the San Fernando station (2016-2019).

	2016				2017				2018			2019		
Mon.	**LEO**	**LAG.**	**HEO**	**Inactive collab. objects**	**LEO**	**LAG.**	**HEO**	**Inactive collab. objects**	**LEO**	**LAG.**	**Space Debris**	**LEO**	**LAG.**	**Space Debris**
Jan.	99	3	2	1	53	4	0	0	0	0	2	38	3	46
Feb.	0	0	0	0	27	0	0	5	0	0	0	40	2	50
Mar.	9	0	0	0	96	0	0	9	0	0	0	55	12	59
Apr.	159	4	4	6	40	4	4	12	2	4	33	24	0	45
May	191	0	0	23	121	0	0	19	41	14	166	67	18	47
Jun.	340	3	0	39	101	3	0	13	37	10	80	65	7	35
Jul.	231	0	0	45					7	3	74	17	11	86
Aug.	291	26	0	43					13	10	39	141	23	85
Sep.	102	2	1	14					25	0	85	49	35	19
Oct.	65	2	0	29					30	5	46	12	51	0
Nov.	19	0	0	8					15	1	26	33	23	0
Dec.	64	0	0	20					40	3	60	30	5	0

System Improvements

Along 2016 it was noted a progressive deterioration in the state of various components, with the corresponding lost in performance. Likewise, between January and February 2016, mirrors were re-coated. In the month of April 2017, we checked the optical components to prepare the station for an SST evaluation campaign that finally took place in the month of June. Once this campaign ended, the laser bench was dismantled. We received a new laser bench (EKSPLA NL317 NS) in July 2017. This laser bench was specially prepared for tracking non-collaborative objects. Between August to December, 2017, a series of severe modifications were carried out aimed to integrate the new laser bank. Finally, in November 2017, first echoes were obtained from non-collaborative objects. In December 2017 we received the new laser bench. It was an EKSPLA PL2251 PS. This laser bench was conceived to fulfil normal active satellite tracking under ILRS rules.

During 2018, actions continued to improve and update the laser tracking system on non-collaborative objects. This leads to building new software to control the new laser bench. Likewise, air safety control software was developed. We included OCR readers that provided azimuth and elevation data, as well as sound alarms indicating the presence of aircraft into a pre-set safety sector at both sides of the laser beam while shooting. During the first semester, actions were carried out to put into operation the new picosecond laser bank. In March 2018, after a period of abnormal behavior the SPAD sensor is disassembled and sent to the Graz Observatory to be repaired. We received it once repaired on the 20th of that month.

On February 26, 2019, a new SAP-500 sensor was received. It was specific for space debris detection. A major issue affected the station from June to December. Our C-SPAD didn't work properly. The signal to command the reception of photons was not received properly. As the issue remained and was not solved we started developing a new system based on Programmable Logic Technology (FPGA board). On December 23, 2019, this new system became operative.

Figure 8-72. The laser bench installed at the San Fernando SLR station.

Current Challenges and Future Plans

Our main goal for the 2017-2019 period was to put into operation the new picosecond laser bench and join again the ILRS activities. Next we plan to change the telescope mount, including new absolute encoders. This will allow us to achieve 2 arc seconds as angular precision. This process was intended to start throughout the year 2020. Due to the current circumstances (COVID-19) the start remains uncertain.

Station Personnel

- Manuel Catalán, Head of Geophysics Department (mcatalan@roa.es)
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Sejong, Republic of Korea

Author: *Hyung-Chul Lim*
Responsible Agency: Korea Astronomy and Space Science Institute

System: SEJL/7394
Location: Sejong, Republic of Korea
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Station Operations

The Korea Astronomy and Space Science Institute has been operating the Sejong station since 2015 for the researches of space geodesy, geophysics and precise orbit determination. The Sejong station, the first SLR station in Korea, is located at Sejong city, administrative capital of Korea, for establishing the core station of Global Geodetic Observing System (GGOS). It had been continuously operated for 24 hours until the middle of 2018, but now is being operated only for night due to the limited budget of station operation.

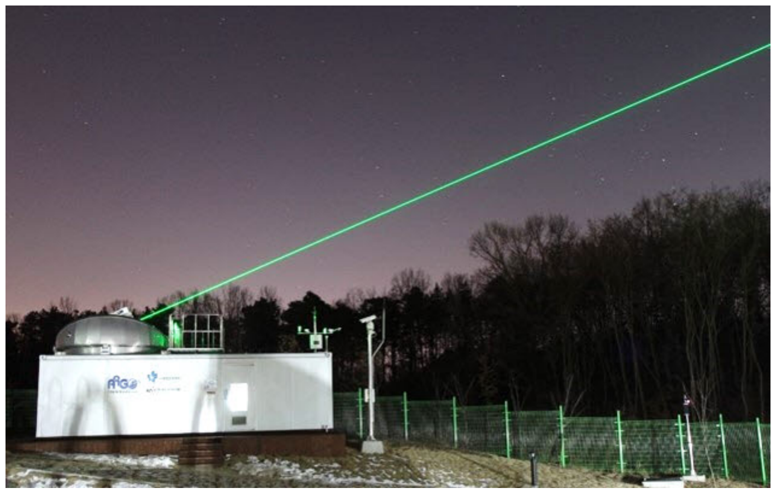

Figure 8-73. Sejong SLR system.

System Improvements

The SLR system is designed to enable kHz laser ranging in both daytime and nighttime tracking of satellites at altitudes between 300 km to 25,000 km. It has a bi-static optical path employing the 40 cm receiving and 10cm transmitting telescopes, and its repetition rate is 5 kHz to research the satellite spin dynamics.

The RGL-532 model of Photonics Industries (USA) is used for the laser system, which is an Nd:YAG pulse laser: 532nm, 2.5 mJ/pulse, 50 ns pulse width, 5 kHz repetition rate, 0.56 mrad far-filed divergence in full angle, 1.26 M2. The optoelectronic controller generates a laser fire command and the range gate (RG) for C-SPAD activity based on the predicted TOF, which is implemented by the field programming gate array (FPGA) board for a fast functional operation. But in the case of ground calibration, it generates a laser fire command and the RG directly without any information of time-of-flight (TOF) because the stop pulse arrives at the C-SPAD preceding the RG signals due to the short distance of the ground target. The SLR system uses the A033-ET model as an event timer which records the epochs of start and stop signals and then puts them into buffer for the implementation of kHz laser ranging.

The laser safety issue is very important in Korea. So, the SLR system uses a radar to provide a means of detecting aircrafts before they intersect a transmitting laser beam which can damage eyes of pilots. The radar pedestal is slaved and bore sighted to the laser-transmitting telescope. If the radar detects aircrafts or it is not synchronized with telescope direction, it sends a signal to the laser system to block the transmitting laser beam.

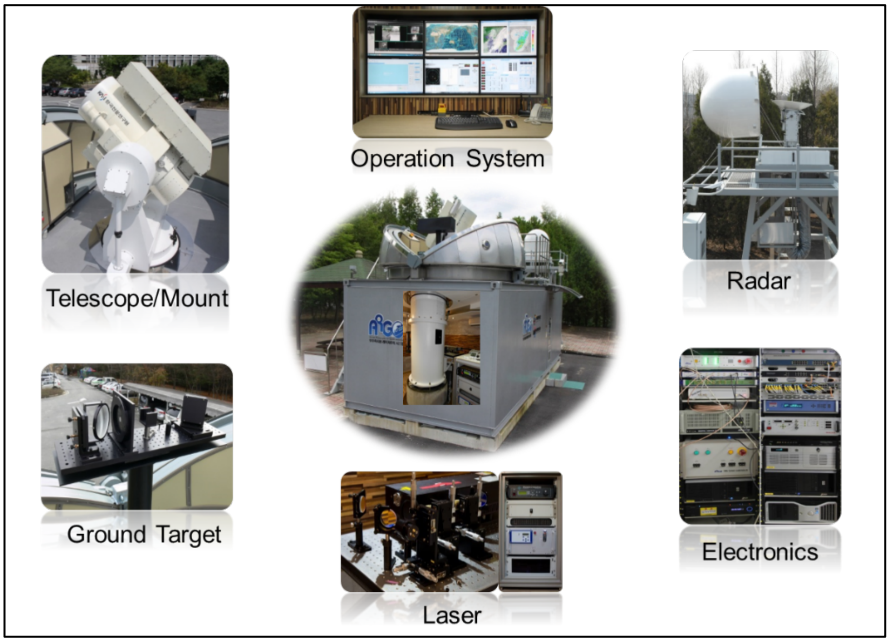

Figure 8-74. Configuration of subsystems of the Sejong SLR system.

Current Challenges and Future Plans

The Sejong station is the member of ILRS tracking network as well as the core station of GGOS which consists of Very Long Baseline Interferometry (VLBI), Global Navigation Satellite System (GNSS) and SLR system. The VLBI system has a 22m Cassegrain antenna, a hydrogen maser atomic clock and a four-channel receiver using 2, 8, 22 and 43 GHz frequencies. There are a lot of survey monuments and pillars inside the core station. So, the local tie survey will be completed in 2020 and then the survey results will be released for a contribution to the International Terrestrial Reference Frame (ITRF).

Station Personnel

- Mansoo Choi (Project Manager)
- Seung-Yeol Yu (Optical Engineer)
- Eunseo Park (Scientist of Data Processing)
- Ki-Pyoung Sung (Software Engineer)

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Shanghai, China

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System: SHA2/7821
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Station Operations

The Shanghai SLR station is located at the top of Western Sheshan mount in the city of Shanghai, China, close to the Sheshan Church. The Shanghai SLR station operates about 20 hours per day (during clear skies), routinely performing 1 kHz SLR measurements. The total passes are over 5000 for tracking LEO, LAGEOS, MEO, and GEO satellites during the 2016-2018 time period with ranging precision on LAGEOS and Starlette at about 7-8mm. The technologies of space debris laser ranging, infrared SLR measurements, and laser time transfer are also developed by using the standard SLR system.

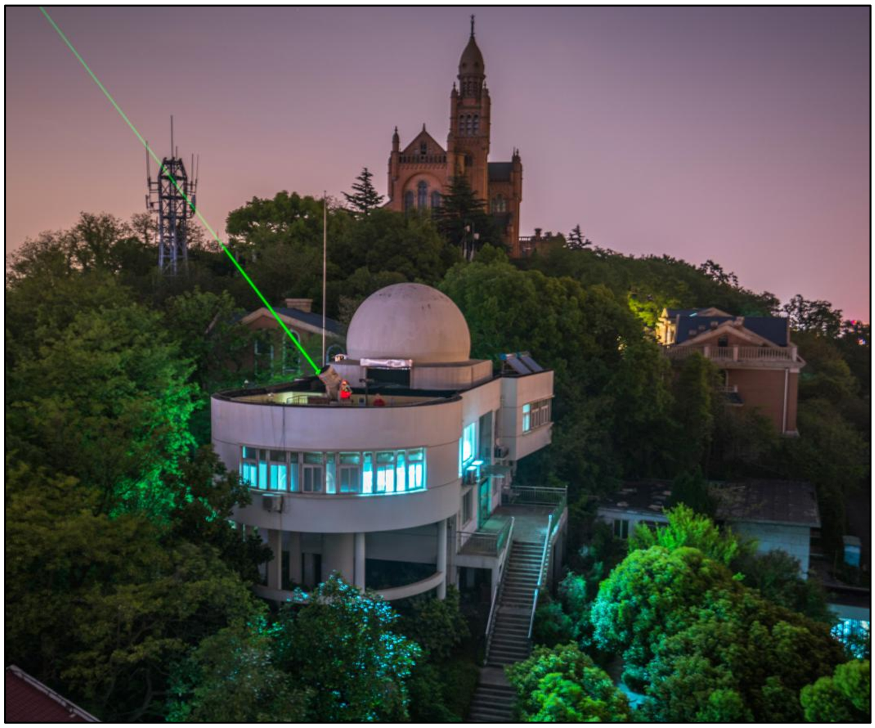

Figure 8-75. Shanghai Astronomical Observatory's SLR system.

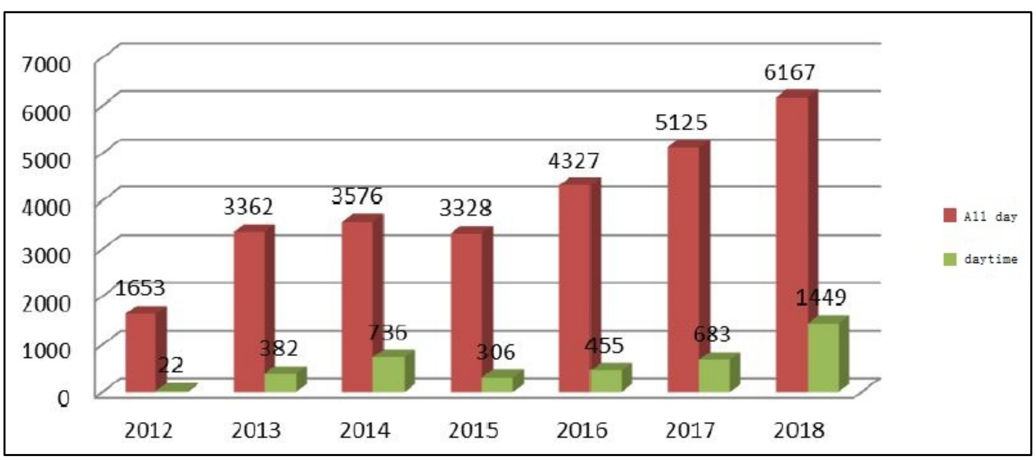

Figure 8-76. Observation statistics from the Shanghai SLR system since 2012.

System Improvements

- Improvements of data quality of ranging to the LAGEOS satellites: The long-term stability, short-term stability, and normal point accuracy have been improved from more than 10mm, 20mm and 2.0mm to less than 5mm, 10mm and 1.0mm by updating the SLR system, such as the shift of timing device into the clean room, changing the signal cables, and calibration.

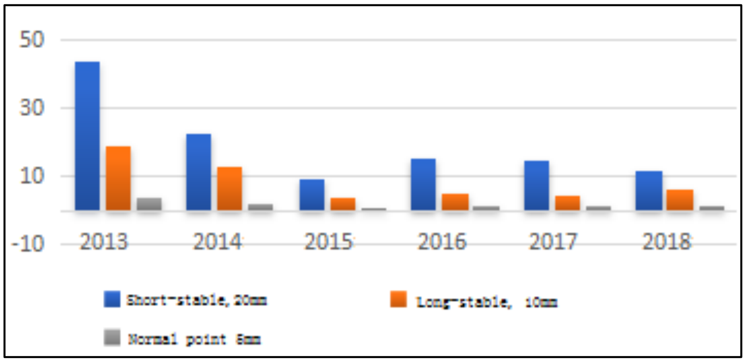

Figure 8-77. LAGEOS satellite's stability at Shanghai astronomical observatory's SLR since 2013.

- 4kHz repetition rate SLR measurements: Updating range gate generator and laser system with repetition rate of 4kHz, power of 3W of wavelength of 532nm; 4kHz SLR measurements are performed to improve the amount of laser data and precision of the normal points.
- Pico-second-laser tracking space debris: The pico-second laser tracking of space debris targets was achieved with a 4.2W double-pulse 532 nm pico-second laser at the pulse repetition frequency of 1kHz; compared with the nanosecond laser system, the advantages of pico-second laser signal are apparent in the aspect of laser divergence, far field pattern, and atmospheric effect.
- Bilateral SLR measurements to space debris: Through solving the synchronization of range gate and timing system between two SLR telescopes with the distance of 2.5km, the bilateral SLR measurements with similar two systems of 60cm telescopes to space debris was performed with the measured range of more than 1000km.
- Infrared SLR to space debris: Updating the high power laser system with the output of 1064nm laser signal, the infrared SLR to space debris was successfully realized by using the infrared detectors and laser beam guiding camera.
- Transportable cabin-based SLR system: One set of transportable cabin-based SLR systems with 60cm aperture telescope which is under development in Shanghai SLR station during 2018-2020, including the transportable cabin, tracking telescope mount, laser system and SLR control system; the potential working sites will be located in the northwestern China in the 2020.
- Development of new generation of Laser Time Transfer: The project of Laser Time Transfer (LTT) in the Chinese space station is underway in order to implement LTT measurements between ground and space station. The LTT payload is being developed by the Shanghai SLR station; the design of the detector and timer, the optical design are preliminary tested.

Current Challenges and Future Plans

In the next two years, Shanghai Astronomical Observatory's SLR station are planning to do the following activities:

- Routine SLR measurements with 1064nm wavelength with high precision
- Two color (1064nm/532nm) SLR measurements

- Developments of automated SLR measurements
- Space debris laser ranging with large energy of burst pulses pico-second laser system at 1 kHz

Station Personnel

- Zhongping Zhang: Director of SLR station
- Zhibo Wu: Manager, electronic
- Juping Chen: Electronic, system
- Haifeng Zhang: Data processing, software
- Pu Li: Mechanical
- MingLiang Long: Laser, optics
- Huarong Deng: Optics, system
- Yan Li: Software, mechanical

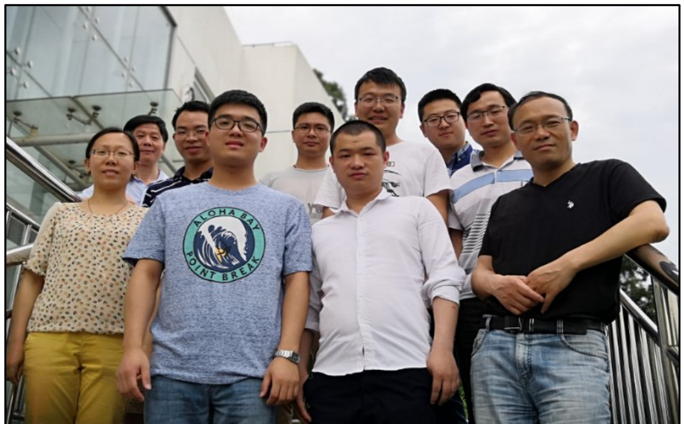

Figure 8-78. Shanghai SLR station staff and graduate student.

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Simosato, Japan

Authors: *Noritsune Seo, Shun-ichi Watanabe*
Responsible Agency: Hydrographic and Oceanographic Department, Japan Coast Guard

System: SISL/7838
Location: Shimosato Hydrographic Observatory (SHO), 1981, Shimosato, Nachi Katsuura-cho, Higashi Muro-gun, Wakayama 649-5142, Japan
Latitude: 33.5777° N, Longitude: 135.9370° E, Elevation: 62.44 m

Station Operations

The Shimosato Hydrographic Observatory (SHO) is located in the south of Kii Peninsula, central Japan, the southernmost part of the Honshu Island (the main island in Japan). Satellite laser ranging observations are routinely performed for 15-18 hours every day from 00:00 UTC (09:00 in JST) with 30-ps laser pulse (wavelength of 532 nm) oscillating at 1 kHz (at a maximum) at 3 mJ output. Recently, the Shimosato system has had difficulty with daytime observations.

Figure 8-79. Simosato laser ranging station.

System Improvements

In the SHO, the laser system, as well as the associated equipment and control unit, were updated in the October through December 2018 timeframe, i.e., from a flash-lamp-pumped YAG to a diode-pumped YAG.

Current Challenges and Future Plans

It is necessary to improve the laser ranging accuracy at the station, which is, of course, an important and common issue at all stations. It is also needed to solve the above-mentioned issue related to the difficulty in daytime ranging in our station.

Station Personnel

- Noritsune Seo: Chief
- Hidekazu Inoshiro: Deputy Chief
- Tomohiro Kinugasa: Staff member
- Masahito Nakanishi: Staff member

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Stuttgart, Germany

Author: *Ewan Schafer*
Responsible Agency: German Aerospace Center (DLR) e.V.

System: UROL/7816
Location: Stuttgart, Germany
Latitude: 48.7824° N, Longitude: 09.1964° E, Elevation: 399 m

Figure 8-80. Twilight inside the dome at UROL.

Station Operations

The Uhlandshöhe Research Observatory (UROL) is operated by the Space Debris/SSA research group of the German Aerospace Centre's Institute for Technical Physics. The site was built as a test-site for space debris research, and this objective led to the development of the UROL SLR station.

UROL is located on a hill, only a few 100 meters from Stuttgart's main train station. The site is leased by DLR from the 'Schwäbische Sternwarte e.V.' amateur astronomy club, which has had a presence there since 1922, when the tower and dome (now a listed building) was constructed.

2016 – 2018 was a very eventful period for UROL. The station achieved first returns in December 2015 and joined the ILRS as an Engineering Station in 2017. Although, there are currently no routine SLR operations at UROL, the station is operated on a campaign by campaign basis.

Because tracking is performed closed-loop, using a tracking camera, the station is limited to night-time operations only. UROL is capable of SLR to LEO and GNSS, but not lunar ranging.

System Improvements

The station operates at 1060.8 nm and is unique in the ILRS in using an optical fiber, rather than a coudé path to couple the laser to the transmitter.

Fiber-coupling has resulted in a reduced cost and complexity system which is easier to maintain and upgrade[1]. A drawback of the current configuration at UROL is that long duration pulses (10 ns) are required to reduce the peak power density sufficiently to avoid damage to the optical fiber. The divergence of the transmitter is also relatively large, owing to the use of a multi-mode fiber.

The result of this is that UROL has relatively poor single shot accuracy of around 60 cm, and return ratios of around 0.1% for LAGEOS. To compensate for the low single shot accuracy, the system uses very high repetition rate and in 2018 DLR began operating the station at 100 kHz.

At these high repetition rates conventional pulse collision avoidance becomes difficult, and so the station is operated in 'Burst Mode', where the laser is gated into bursts which are one time-of-flight long. This results in an effective pulse repetition rate which is approximately half of the laser's true pulse repetition frequency. UROL currently operates at 200 kHz pulse repetition frequency (100 kHz effective).

The increased performance at 100 kHz allows UROL to measure LAGEOS normal points with precision on the order of 10mm, and led to UROL's first successful ranging to GNSS in 2018.[2]

For reference, the parameters of UROL's laser as of 2018 (JenOptik JenLas fiber ns 70) are shown below:

Center wavelength:	1060.8 nm
Spectral Bandwidth (FWHM):	4 nm
Pulse energy (at laser):	80 µJ
Pulse energy (at transmitter):	50 µJ
Pulse duration:	10 ns
Repetition rate:	200 kHz (100 kHz effective)

In 2016, DLR developed "Orbital Objects Observation Software (OOOS)", a cross-platform, modular and hardware-independent control software and user interface written in Python 2.7 (with some supporting functions in C)[3]. The project was ported to Python 3 and made open source in 2018.

Current Challenges and Future Plans

The choice of single photon detectors which are sensitive to 1060.8 nm light is limited. The IDQ400 detector used at UROL has a relatively small detector size of 80 µm which results in a small field of view for the detector. This field of view is smaller than the blind-pointing accuracy of the system, which is why UROL is currently not capable of blind-tracking, and by extension not capable of ranging during daylight.

Improved fiber coupling: The limitations of the optical fiber, mentioned in the previous section, are by no means hard limits for fiber-coupled SLR. The divergence of the transmitter would be greatly improved by coupling into a single-mode, rather than multi-mode optical fiber. The peak-power limit, which necessitates long duration pulses, could similarly be improved through the use of a hollow core fiber or LMA (large mode area) fibers.

In principle the repetition rate of the laser can also be increased further, before range ambiguity effects become significant. The JenLas laser can operate at repetition rates up to 1 MHz and we intend to

[1] *Hampf, Sproll, Wagner et al. (2016). First successful satellite laser ranging with a fibre-based transmitter. Advances in Space Research. 58. 10.1016/j.asr.2016.05.020.*

[2] *Hampf, Schafer, Sproll et al: Satellite Laser Ranging at 100 kHz pulse repetition rate, CEAS Space Journal (2019).*

[3] *Hampf, Sproll, Hasenohr (2017) OOOS: A hardware-independent SLR control system. ILRS Technical Workshop, 02.-05. Oct. 2017, Riga*

investigate extremely high repetition rates, where the ambiguity problem can be tackled by using chirped pulses. This will likely only become feasible when the fiber is improved to allow higher power.

DLR is currently experimenting with fiber coupled detector(s) which will allow for more complex & heavier instruments with no loss of tracking performance.

Improved aircraft safety: A considerable amount of work is being carried out to ensure the safe operation of lasers in open airspace. UROL is located only 11 km from STR international airport. This, combined with UROL's proximity to the city center, results in aircraft frequently flying low, close to the station, making laser safety critically important.

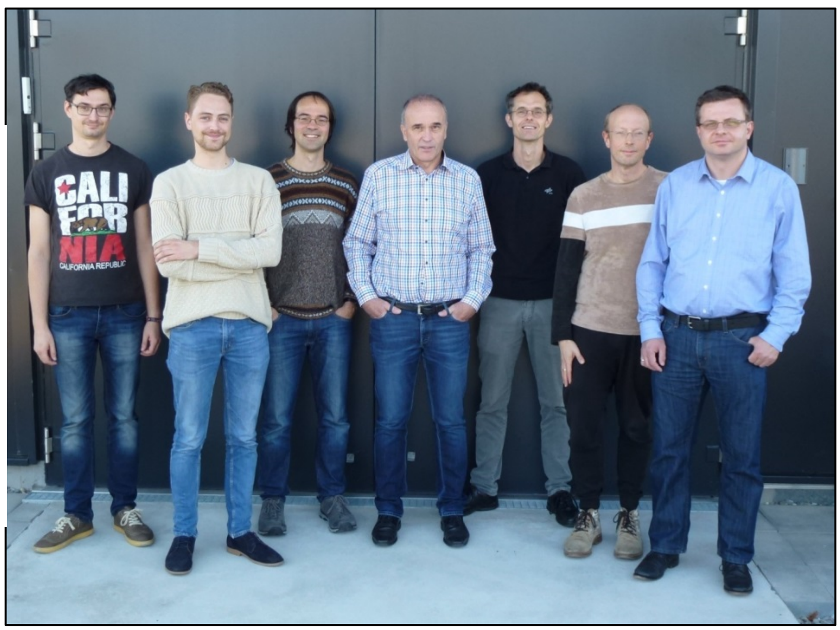
There is an increasing probability that UROL may be decommissioned within the next two years. The lease on the site will expire in 2020, and we are therefore winding down station operations. The technology developed for UROL and lessons learned are being applied to DLR's 3 new SLR projects: miniSLR, STAR-C, and MS-LART.

Station Personnel

- Ewan Schafer: Station manager
- Daniel Hampf
- Paul Wagner
- Wolfgang Riede: Head of department

Figure 8-81. The staff of the Institute for Technical Physics, Active Optical Systems, SSA/Space Debris Research Group.

From left to right: Paul Wagner, Ewan Schafer, Daniel Hampf, Wolfgang Riede, Jens Rodmann, Stefan Scharring, Gerd Wagner



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Svetloe, Russia

Authors: *Iskander Gayazov, Viktor Mitryaev*
Responsible Agency: Institute of Applied Astronomy (IAA RAS)

System: SVEL/1888
Location: Svetloe, Leningradskaya District, Russian Federation
Latitude: 60.5332°N, Longitude: 29.7805°E, Elevation: 69 m

Station Operations

The Svetloe SLR station (SVEL/1888) is located in the Leningradskaya region near Saint Petersburg at one of three observatories of the "Quasar-KVO" VLBI network. The observatory is a co-location site with two radio telescopes (RT-32 and RT-13), "Sazhen-TM" SLR system, GNSS receivers, and a water vapor radiometer. The SLR system has day and night cameras and holographic filter (0,1 nm bandpass) which allows all day functioning. In spite of a relatively small aperture of the telescope (25 cm) and low pulse energy (2,5 mJ), the laser system is capable of conduct observations of satellites with the orbits up to 40000 km.

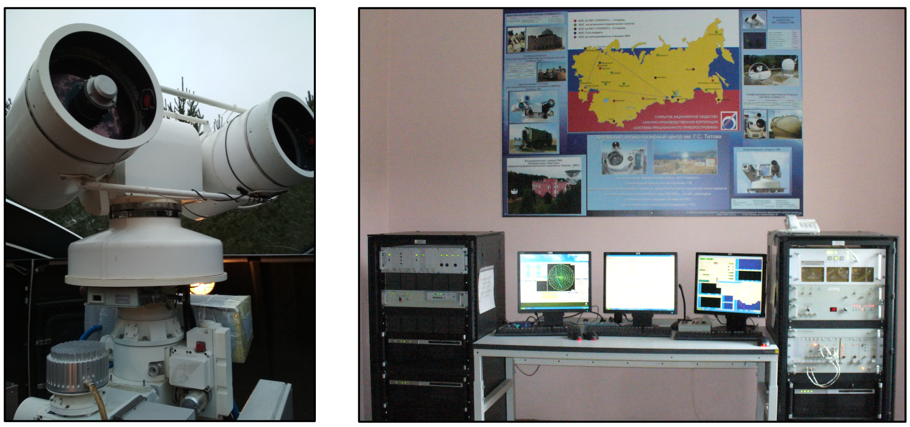

Figure 8-82. "Sazhen-TM" laser system (left) and the laboratory equipment of the system (right).

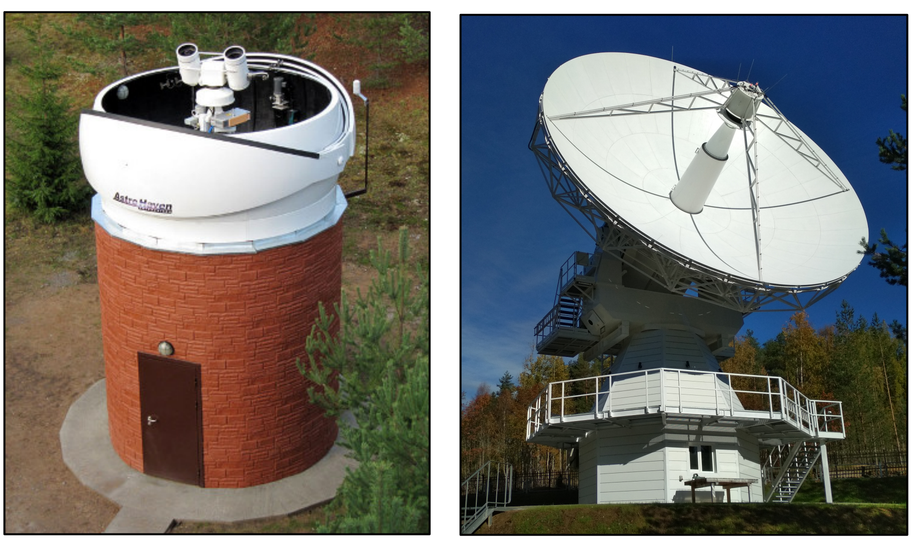

Figure 8-83. The SLR system building (left) and VGOS antenna of RT-13 radiotelescope (right).

System Improvements

In 2018 new star calibration software was installed at the station. This software allows staff to make angular corrections automatically and improves tracking capabilities enormously, in daytime especially.

Current Challenges and Future Plans

The main problem is the obsolescence of the laser emitter of the system. This leads to the need to repair the laser every few years. The current laser has a pulse width worse than 300 ps. This is the main reason for the current level of single shot RMS (3-4 cm). The main task for the future is to modernize the system and improve the RMS up to 1 cm. To reach this goal the replacement of the laser with new equipment which has a ~50 ps pulse width is planned. The next step is to replace the time interval counter and to increase the repetition rate from 300 Hz up to 600 Hz. These plans are expected to be implemented after 2020.

Station Personnel

The laser system at the observatory is maintained by the staff of operators, who work in shifts (two operators per shift). All operators are capable to carry out both VLBI and SLR observations even if they occur at the same time. The observation results are sent via network transmission to the processing center at IAA (Saint-Petersburg). There ,the data are processed and sent to EDC and other users. Repairs of the system and overall operation are conducted by the lead engineer Viktor Mitryaev.

The station operators are as follows:

- Victoria Baikova
- Olga Isaenko
- Vera Kirillova
- Natalia Slobozhaninova
- Julia Shumilova
- Olga Gribova
- Maria Kirillova
- Oksana Kuzmina
- Tatiana Oiya

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Tahiti, French Polynesia

Author: *Yannick Vota*
Responsible Agency: Université de la Polynésie Française

System: THTL/7124
Location: Tahiti, French Polynesia
Latitude: 17° 34’ 36.6’’ S, Longitude: 149° 36’ 22.3’’ W, Elevation: 99 m

Figure 8-84. The MOBLAS-8 system located in Tahiti, French Polynesia.

Station Operations

The station operates 16 hours/day, 4 days/week.

System Improvements

1. Two Harmonic Drives EC-1890B were installed in the radar and the resolver core nuts were secured with blue Loctite. The radar was aligned and verified using a recently installed cell tower and a peak on the distant island of Moorea. The alignment was verified by tracking one ferry boat and by tracking two groups of balloons carrying aluminum foil reflectors. No airplanes were tracked above twenty degrees, since no airplanes fly directly over the island and airport. Commercial airplanes landing and taking off never exceed the twenty degree elevation limit set for laser tracking.
2. Dual Power Amplifier EC-1559B was installed and verified operational.
3. MET-4 Meteorological System was relocated from the side of the Tracking Trailer and away from the Chiller exhaust and heat of the trailer. The new location is an extended pole on the back fence. The height of the barometer sensor was maintained to the center of the tracking mount.

4. ARSU Repair (Mantis 1075) The Amplified Receive Selection Unit (ARSU) was repaired by changing two cards and an amplifier module. The amplified mode was verified by performing valid amplified calibrations.
5. Encoders: The two system encoders and one spare were rebuilt with non-corrosive integrated circuits and verified in the Mount Position and Control System (MPACS).
6. Cable Arm: Since a lot of paint was missing from the cable arm . It was painted flat black to reduce the laser reflections when performing tracking operations. Brackets were installed on the cable arm to hold the cables.
7. Receive Cable: The bad receive cable was replaced and this reduced calibration RMS from 6.8 to 5.6 millimeters. The station has two additional spare receive cables in stock.
8. Installed the Event Timer EC-1169B and verified the input signals to the Event Timer (ETM) and Event Timer Computer (ETC). During verification a software error indicated a timing board failure in the ETC computer.

Station Personnel

Figure 8-85. Tahiti station personnel: (left to right), Jean-Pierre Barriot (station manager), Yannick Vota, Youri Verschelle, James Levreault (technicians).

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Tanegashima, Japan

Authors: *Shinichi Nakamura, Takehiro Matsumoto, Takushi Sakamoto, Kazuhiro Yoshikawa*
Responsible Agency: Flight Dynamics Team, JAXA

System: GMSL/7358
Location: Tanegashima, Japan
Latitude: 30.5565° N, Longitude: 131.0154° E, Elevation: 141.0967 m

Station Operations

The Tanegashima SLR station is located southwest of Japan and operated by remote control from Tsukuba Space Center. The system has been operated since April 1, 2004, and is capable of ranging to various satellites from LEO to GEO.

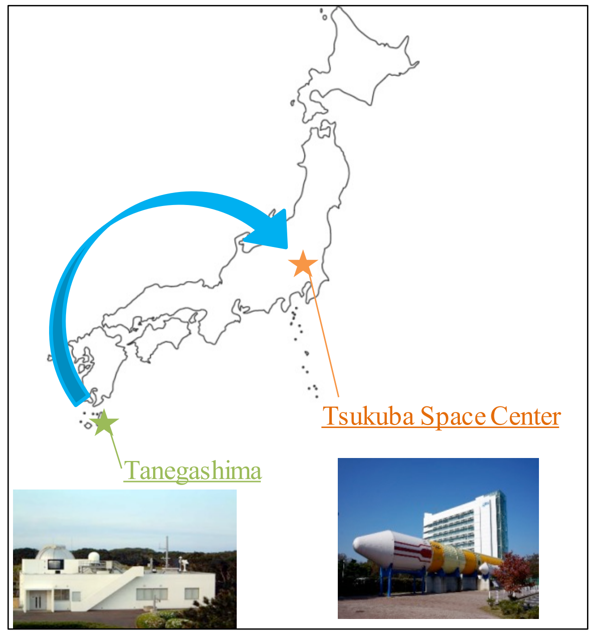

Figure 8-86. Tanegashima SLR station.

System Improvements

In 2012, due to SLR system problems, the Tanegashima station fell into the category of a "quarantine" station. After that, the station was used for tracking satellites, especially LAGEOS-1, LAGEOS-2, and LARES. During 2016-2018, the station was intensively tracking those satellites. However, another mechanical issue (failure of the focus mechanism of the telescope), prevented the station from returning to the operational station category. After the problem was fixed in July 2017, the station once again became capable of obtaining ranging data efficiently. In 2016, the station acquired 20, 5, and 19 passes of LAGEOS-1, -2, and LARES respectively. In 2017, the number improved to 16, 28, and 30. Unfortunately, due to the bad weather conditions, the Tanegashima station has not returned to the normal, operational category yet. Currently, Tanegashima station is still tracking those satellites, and its main focus now is to track QZSS to support the Japanese government by submitting CRD by email.

Current Challenges and Future Plans

In October 2017, a challenge to track space debris with high orbit mode, that is, 250mJ, 10Hz, 250 ps pulse width, was conducted several times. We succeeded in tracking space debris a few times, and the RMS of residuals (O-C) was 1 – 2 [m]. It was found that it is not so easy to track space debris because of the weak return rate and the bad accuracy of the orbital prediction.

From the middle of 2018, JAXA started developing a new SLR station where recent trends in SLR community such as kHz ranging, equipment downsizing, and 1064 nm wavelength will be introduced. The new SLR station will be built at the Tsukuba Space Center, where the weather conditions are much better than that of Tanegashima. The bid was finished in December 2018, and we are now in the design phase. According to the master schedule, the new station will start operating in April 2021, when the Advanced Land Observing Satellite 4 (ALOS-4) requires precise orbit determination.

Station Personnel

In 2019, our Flight Dynamics Team at JAXA, consisting of a manager and five energetic staff members, will take over the research and maintenance of SLR from the Network and Communications Team. We will do our best to meet ILRS expectations.

Figure 8-87. Tanegashima SLR station staff, left to right: Takushi Sakamoto, Takehiro Matsumoto, Yuki Akiyama, Shinichi Nakamura, and Kazuhiro Yoshikawa.

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TROS Mobile System, China

Authors: *SLR Group*
Responsible Agency: Institute of Seismology, China Earthquake Administration, Xinjiang Astronomical Observatory , Chinese Academy of Sciences

Station Operations

Supported by the Crustal Movement Observation Network of China (CMONOC), the Institute of Seismology, China Earthquake Administration (ISCEA) reached a cooperation agreement with Xinjiang Astronomical Observatory, Chinese Academy of Sciences (XAO, CAS), to establish a SLR site in XAO with TROS1000 under the coordination of Chinese SLR network.

TROS1000 is a 1-m-diameter mobile Satellite Laser Ranging (SLR) system with a damping system for transportation and a detachment support system for observations (see Figures 8-88 and 8-89).

On August 29, 2019, TROS1000 set out from Xianning, Hubei Province, crossed about 3400km, passing through five provinces of Hubei, Shanxi, Ningxia, Gansu and Xinjiang. After a seven day journey, overcame various road conditions, TROS1000 reached Nanshan Observatory of XAO.

On September 19, 2019, TROS1000 successfully carried out the first day of observations, respectively observing high, medium and low orbit satellites, which is also the first time to obtain kHz mobile SLR data in Western China. As of October 13, 2019, the total number of observation quantities is 123 passes, including 69 passes of LEO satellite, 22 passes of LAGEOS satellite, 32 passes of HEO satellite. The effective observation days were 14 days, The maximum observation passes per day was 18 passes. The single accuracy of LEO satellite is better than 15mm, that of LAGEOS is better than 15mm, and that of HEO satellite is better than 20mm.

Figure 8-88. TROS1000 measurement.

Figure 8-89. TROS1000 system.

Station Personnel

Figure 8-90 shows the crew of TROS1000.

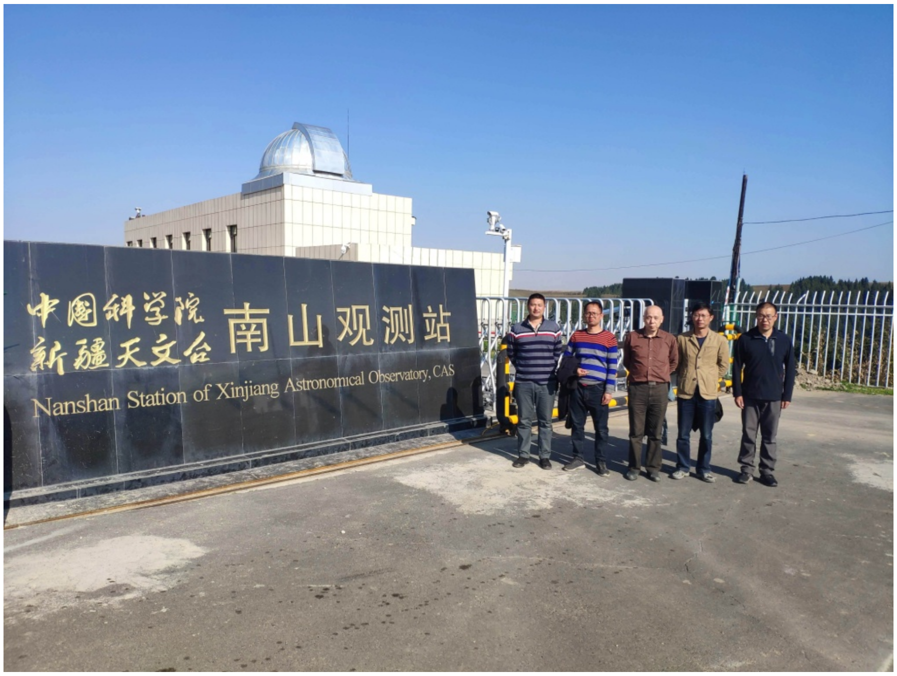

Figure 8-90. The crew of TROS1000.

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P.R. CHINA

Wettzell, Germany (WLRS and SOS-W)

Author: *Johann Eckl, Stefan Riepl*
Responsible Agency: Federal Agency for Cartography and Geodesy (BKG)

System: WLRS/8834 and SOS-W/7827
Location: Wettzell, Germany
Latitude: 49.1449402° N, Longitude: 12.8781000° E, Elevation: 663.174m

Station Operations

The Geodetic Observatory Wettzell is a fundamental station that operates all four major geodetic techniques, namely SLR, VLBI, GNSS, and DORIS. SLR is carried out by two independent system, the WLRS (Wettzell Laser Ranging System) and the SOS-W (Satellite Observing System-Wettzell). Wettzell is located in the south-east of Germany, in the Bavarian Forest. The WLRS, as well as the SOS-W system, are fully dedicated to geodetic observations. Therefore, Satellite Laser Ranging measurements are performed on a 24/7 basis, whenever the weather permits. Observations are conducted from the laser team with support from colleagues from other disciplines at the Geodetic Observatory Wettzell and student observers.

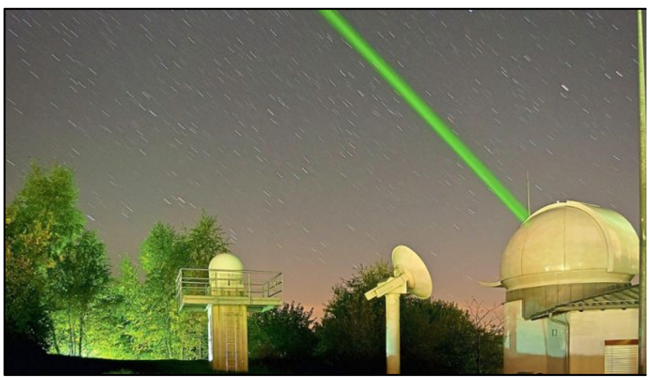

Figure 8-91. WLRS operating at night.

Figure 8-92. SOS-W laser dome.

WLRS: After two years with a moderate number of passages in 2016 and 2017, during 2018 a new passage record with 9516 passages could be obtained due to exceptionally good weather. In 2018 successful Lunar Laser Ranging (LLR) tests were also conducted in the near-infrared. From 2018 on LLR is also considered as a permanent task in the schedule of the WLRS. Due to the poor atmospheric condition at Wettzell, typically the air is rather wet and turbulent in this area, LLR is performed at an elevation of the Moon, above 50 degree only.

SOS-W: During the report period 2016 to 2018 the SOS-W, situated in Wettzell and co-located with WLRS and RTW (VLBI), was operated in 12/7 mode predominantly during the night. After the last issues concerning the telescope transmit optics were resolved in 2015, the system was running stable throughout the reporting period, with an exception of the summer 2017, where an issue occurred with the azimuth drive gear box, which required a modification of the lubrication concept. Investigations on how to resolve that issue in a permanent manner are still ongoing today.

System Improvements

SOS-W: Since November of 2016 the SOS-W operates exclusively in autonomous mode, i.e., the SLR system performs automatic scheduling and interleaving based on an algorithm, which was demonstrated at the 2017 ILRS Technical Workshop in Riga. As the primary in sky laser safety system is still a work in progress, operations are restricted to nighttime only. But the impact of switching to autonomous mode can be clearly seen by the improved data yield obtained from a better efficiency, due to the kHz- repetition rate operations.

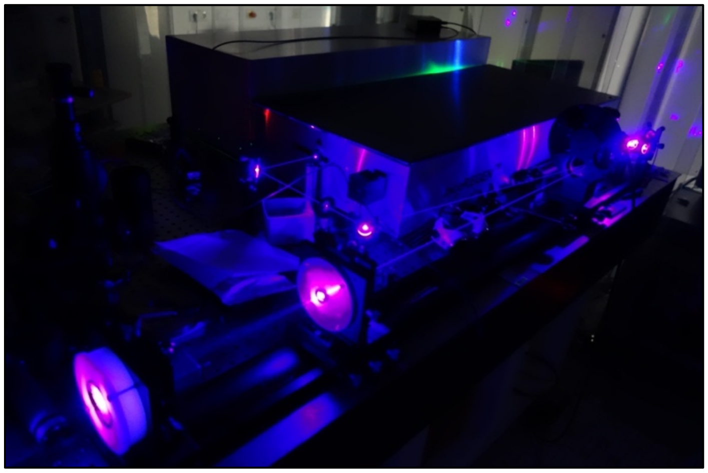

Figure 8-93. Operations of the Ti:Saph laser of the SOS-W.

WLRS: Because the radar-system of the WLRS developed performance issues over the years and because it was not compliant with the VLBI receivers of the TWIN radio-telescopes at the GOW, a new In-Sky-Safety concept was developed. The new safety system consists of sensors optimized for object detection at large and short distances. The primary in-sky-safety method for large distances is a real-time data stream of aircraft positions from the radar network of air traffic control in the region around Wettzell. This method is supported by an ADS-B receiver for redundancy. For short distances, an infrared camera for detecting hot objects in front of the cold atmospheric background was installed as the primary system. All safety methods support each other in a cooperative way on short as well as on long distances.

In 2016, our contribution to the ESA GSTP Project "Accurate orbit determination of space debris with laser tracking/tasking," which was conducted together with the colleagues from Technical University Munich, DLR Stuttgart, Observatory Graz, and ESA Darmstadt, could be finished successfully. The result was a demonstration of the capability of ranging debris targets in diverse configurations like single station, bistatic, multi-static, and with multiple laser wavelengths involved.

In 2017, ranging tests to the ISS were made in preparation of the ELT time transfer experiment. The goal was to identify spurious reflections from other retro-reflectors installed on the ISS. It was found that an additional algorithm is required to discriminate between spurious returns and the true ELT echoes.

In 2018, returns from the lunar retro-reflectors were detected, a long time since the last attempts by the system in the early 90s. The signal strength was close to the expected theoretical value. Usually about 20 to 30 lunar echoes are obtained in a 15 minute observation interval. Since the single shot precision of the WLRS is well below 5 mm, this is, in principle, sufficient to achieve a normal point precision close to or even below 1 millimeter. Unfortunately, the lunar libration causes the lunar reflectors to tilt and as a result to spread the single shot precision of the WLRS – a zero signature target on the Moon would be a great improvement.

Current Challenges and Future Plans

SOS-W: Due to the co-located operations of two laser systems at one site, the work is concentrating on the definition and implementation of a combined in-sky-laser-safety concept. This task includes the commissioning of an infrared camera based safety system, with the capability of detecting aircraft at a distance of up to 50km. Results obtained so far are very promising and operability of the system is expected in 2019. Apart from that, as the SOS-W is designed to support two color laser ranging, a second detector will be installed permanently, permitting two color observations at least to LEO satellite missions.

WLRS: Just recently the WLRS was upgraded to a high repetition rate system, now ranging at 400 Hz on a mono-static telescope. For that purpose, the software and hardware interacting with the DASSAULT event-timing modules had to be rebuilt. Since the WLRS is a mono-static system, a new T/R switch had to be installed in addition. The WLRS can now be operated in a high energy mode for lunar laser ranging or debris ranging and a low energy mode at a repetition rate of up to 400 Hz for all ILRS targets. The system now routinely operates at a wavelength of 1064 nm with the option to operate at 532 nm, if required. Since the energy density at the telescope output is eye-safe at 1064 nm in the low energy mode, eye-safe operation will be possible in the future when safe switching between the operating modes is implemented.

Increasing the repetition rate of the WLRS was the first step towards an autonomous operation of the system. A big effort is now made to finish the work on the new controlling software that allows for autonomous operation of the WLRS.

The LLR capability of the WLRS is still not at the final limit. Additional technical improvements will be implemented to increase the data yield. These may include the use of adaptive optics, the implementation of a wide field of view guiding camera and an optimization of the laser post amplifier. Further improvement is expected when a still existing small scale pointing issue of the telescope is resolved.

Since the ELT mission is intended to start in 2020, the WLRS, as the primary optical ground segment, is currently upgraded to support the mission. This upgrade includes the generation of the “start-epoch” at the sub-picosecond level, the synchronization of the laser fire epochs, and the approval the required laser safety implementation.

Station Personnel

- Torben Schüler: Head of the Geodetic Observatory Wettzell
- Ulrich Schreiber: group leader “Optical Technologies”
- Günther Herold: chief engineer, SLR operations (secondary contact)
- Stefan Riepl: SOS-W system manager (optics, hardware, software, and development) primary contact
- Johann Eckl: WLRS system manager (optics, hardware, software, and development) primary contact
- Theo Bachem: IT expert, system monitoring
- Andreas Leidig: software with focus on in-sky-safety and operating system
- Swetlana Mähler: local ties
- Observer support from other groups of the GOW and student observers

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Website: *http://www.bkg.bund.de*

Wuhan, China

Author: *Jie Zhang, Bobi Peng, Xinghua Hao, Chongchong Zhou*
Responsible Agency: Innovation Academy for Precision Measurement Science and Technology, CAS

System: JFNL/7396
Location: Wuhan, China
Latitude: 49.1449402° N, Longitude: 12.8781000° E, Elevation: 663.174m

Introduction

Satellite laser ranging (SLR) is widely recognized as the highest accuracy technology in the field of modern space ranging, and the measurement precision and accuracy can reach a millimeter order of magnitude. The Wuhan SLR station at the Institute of Geodesy and Geophysics, Chinese Academy of Sciences (CAS) started to work in satellite laser ranging from the end of the 1970s, building the 60cm SLR telescope (WUHL, 7231). It is the one of the earliest institutes which performs research in satellite laser ranging technology and analyzes laser ranging data in China. In the middle of the 1990s, the Wuhan SLR station was moved to the Jiufeng hill at the east side of Wuhan city. Part of the hardware and controlling algorithm was updated at the end of the 1990s, and the performance reached the accuracy of a third generation SLR system. The accuracy of the 60cm SLR telescope reached 1cm to several centimeters.

The Wuhan SLR station began to build a new 1m aperture SLR telescope (JFNL, 7396) in 2015 to replace the old 60cm SLR telescope (WUHL, 7231). The new 1m aperture SLR telescope obtained its first ranging data on September 29, 2018; the system was able to range to all SLR satellites listed on ILRS website. The new system has worked normally since July 02, 2019. The pointing accuracy is less than 2 arc second after corrections were applied to the pointing model, and the tracking accuracy is less than 0.3 arc second (RMS value of O-C).The target calibration accuracy is less than 7mm, and the single shot ranging accuracy for LAGEOS observations is less than 11mm.

Figure 8-94. 60cm (7231, left) and 1m (7396, right) telescope at Wuhan SLR station.

System Operations and Improvements

The 1m aperture SLR system consists of 1m aperture telescope, mount, servo-controlling module, laser transmitting and receiving module, time and frequency module, event counter and computer controlling module, and the block diagram of the SLR system is shown in Figure 8-95. The satellite orbit prediction and laser ranging data processing are carried out in a computer control module. C-SPAD with the performances of single photon detecting sensitivity, high quantum efficiency, time drift compensation and time resolution is used to detect echoes and generate “STOP” signal of event counter. The Latvia A033 event counter is used to measure the time interval between the laser launching moment and photon echoes receiving moment. In order to realize daytime ranging in future, the narrow-band optical filter and powerful light protector will be added in conventional echoes receiving system.

The key parameters of the new 1m aperture SLR system is described as following:

- Laser: 532nm, 1.0mj @ 1kHz
- Event timer: A033, 10ps precision
- Target: ground target with 2 diffuse aluminum sheet, installed on telescope
- Detector: C-SPAD, 25ps jitter, 20% Quantum Efficiency

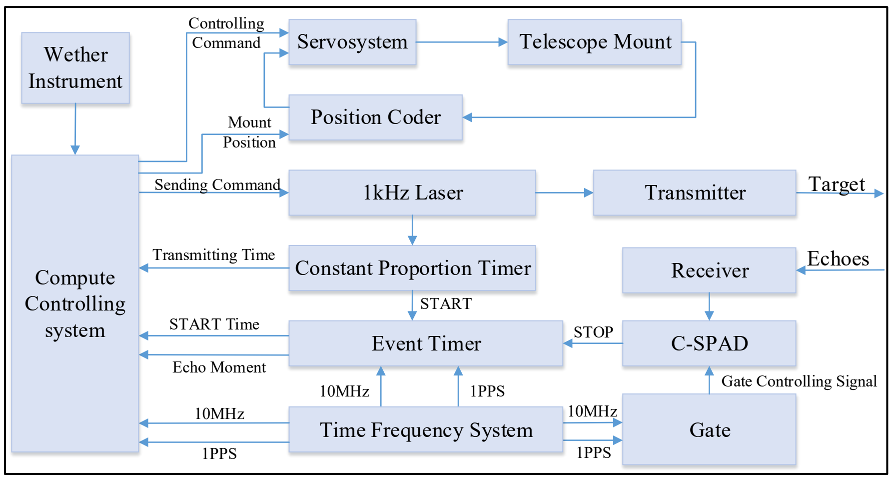

Figure 8-95. The block program of the new SLR system with 1 aperture telescope.

The ranging control software has many functions, including telescope controlling, data identification, pointing tuning, and ranging satellite selection and so on. The software is designed by the Shanghai SLR station, and shown in Figure 8-96. In addition, the post processing software is used to fit ranging data, generate CRD files (normal point and full-rate data) and analyze statistic parameters (range and time bias, rms, skew, etc.).

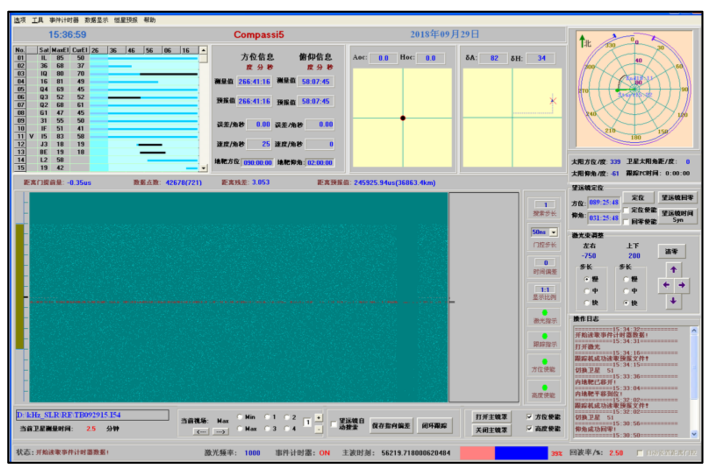

Figure 8-96. The controlling software of Wuhan SLR station.

Observation Results

Figure 8-97 shows the latest observation pass statistics from 2019-04-01 to 2020-03-31 for global SLR stations issued by International Laser Ranging Service (ILRS). The figure shows that the Wuhan SLR station obtained 1353 passes, including 528 low satellite passes, 171 LAGEOS satellite passes, 13 high satellite passes, and 641 global navigation satellite system (GNSS) satellite passes. In this year, the Wuhan SLR station obtained more ranging passes to reach the ILRS baseline of 3500 passes. Figure 8-98 shows that the accuracy of Wuhan SLR station is 10.3mm, and the target calibration accuracy is 6.6mm in this period.

Conclusion

The 1m aperture SLR system had successfully ranged to satellites on September 29, 2018. The system performs routine operations and has submitted laser ranging data to the ILRS data centers since July, 2019. Its performance has reached the baseline of LAGEOS NP RMS and short term stability. However, the problem is a reduced amount of observation passes for Wuhan SLR station. In order to reach the baseline of 3500 passes, the Wuhan SLR station will employ two full time observers this year.

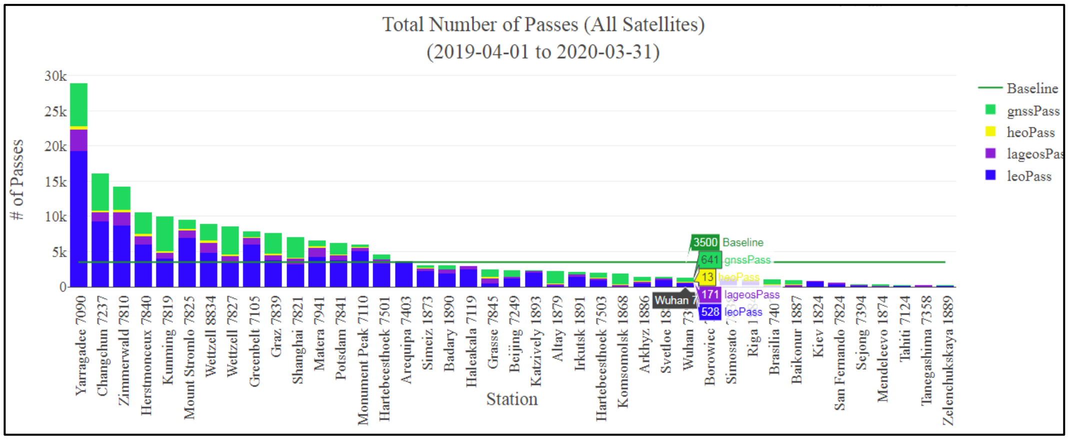

Figure 8-97. Observation passes statistics for global SLR stations.

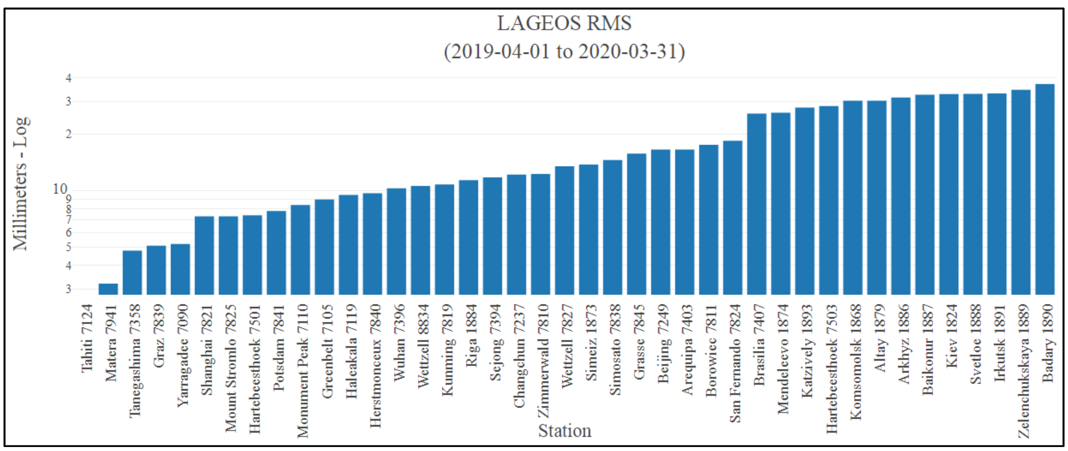

Figure 8-98. Ranging accuracy of LAGEOS satellite for global SLR stations.

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Yarragadee, Australia

Author: *Randall Carman*
Responsible Agency: NASA GSFC/Geoscience Australia

System: YARL/7090
Location: Yarragadee, Western Australia
Latitude: 29.0464° S, Longitude: 115.3467° E, Elevation: 244 m

Station Operations

The MOBLAS-5 system continues operations on a 24x7 basis as part of the Yarragadee Geodetic Observatory. The staff operates the system 12 hour, 4 days on 4 off non-rotating shifts.

The system is performing well and has maintained their position as the premier site for SLR data collection over the reporting period.

The staff also continue to operate the AUSCOPE 12m VLBI antenna in partnership with the University of Tasmania and host Geoscience Australia's GNSS CORs receivers (3+1). The site also includes a DORIS beacon and has hosted GA's FG5 absolute gravimeter three times during 2016-2019.

Figure 8-99. The Yarragadee Geodetic Observatory showing MOBLAS-5 vans with improved safety access, VLBI 12m antenna and two SAR calibration CRs.

System Improvements

The implementation of the NASA/SLR event timer in September 2017, greatly improving the single shot RMS, has been the biggest upgrade in the reporting period. Personnel have also installed safer access stairways to both the MOMS (75cm telescope), platform and instrument van.

During 2016, staff also installed a site-wide 200kVA UPS. This along with their automatic standby generator, means all equipment is much better protected from power outages and transients.

In 2018 Geoscience Australia installed two trihedral Corner Reflectors for SAR calibration.

Current Challenges and Future Plans

Some of the NASA/SLR provided operating software has become seriously limiting due to the greatly increased number of targets. NASA/SLR are working hard to upgrade the operating software but in the meantime the staff continues to develop workarounds to optimize tracking efficiencies. Link margins continue to decrease, most likely due to ageing optic coatings in the transmit and receive paths.

Personnel can already control the SLR system semi-remotely and they continue to work towards being able to operate the system completely remotely and/or semi-autonomously.

NASA/SLR are moving to a full implementation of the event timer whereby the system can operate at 10Hz for all targets.

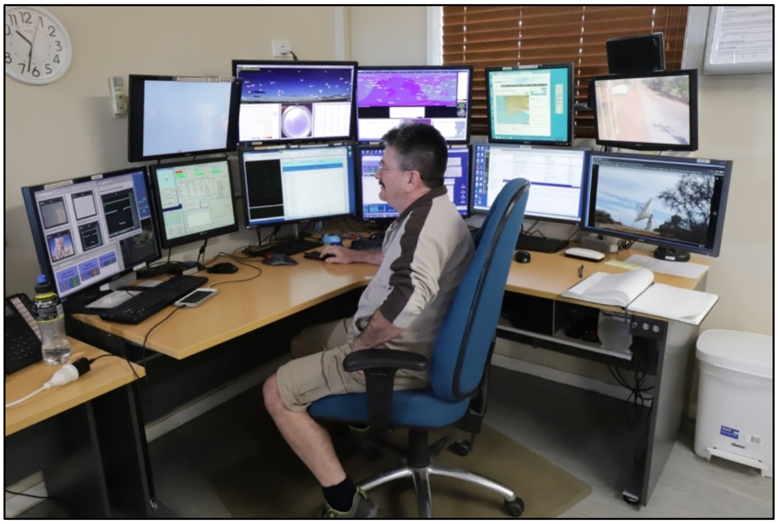

Figure 8-100. The current semi-remote operations console.

Station Personnel

In 2018 Geoscience Australia approved the increase in observatory staff from 6 to 7 and Mr. Sandy Jones was hired to fill the new role of Assistant Station Manager. This addition has greatly improved the ability to cover station staffing when the observers or manager are on leave.

Station staff:

- Randall Carman: Station manager
- Sandy Jones: Assistant station manager
- Peter Bargewell, Dave Essers, John Colley, Michael Wilson: Operations team
- Jack Paff: Facilities manager

Figure 8-101. Yarragadee Geodetic Observatory staff (left to right: Peter Bargewell, Michael Wilson, Dave Essers, John Colley, Sandy Jones, Jack Paff, and Randall Carman).

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Zelenchukskaya, Russia

Authors: *Iskander Gayazov, Viktor Mitryaev*
Responsible Agency: Institute of Applied Astronomy (IAA RAS)

System: ZELL/1889
Location: Zelenchukskaya, Karachaevo-Cherkesskaya Republic, Russian Federation
Latitude: 43.7887°N, Longitude: 41.5654°E, Elevation: 1155 m

Station Operations

The Zelenchukskaya SLR station (ZELL, 1889) is located in Karachaevo-Cherkesskaya Republic (Russian Federation) at one of three observatories of the "Quasar-KVO" VLBI network. The observatory is a co-location site with two radio telescopes (RT-32 and RT-13), "Sazhen-TM" SLR system, GNSS receivers, and a water vapor radiometer. The SLR system has both day and night cameras and a holographic filter (0,1 nm bandpass) which allows for all day functioning. In spite of a relatively small aperture of the telescope (25 cm) and low pulse energy (2,5 mJ), the laser system is capable to conduct observations of satellites with the orbits up to 40000 km.


Figure 8-102. "Sazhen-TM" laser system against the background of RT-32 radiotelescope (left) and the laboratory equipment of the laser system (right).

System Improvements

In 2018 new star calibration software was installed at the station. This software allows the staff to make angular corrections automatically and improves tracking capabilities enormously, especially in the daytime.

Current Challenges and Future Plans

The main problem is the obsolescence of the system's laser emitter. This leads to the need to repair the laser every few years. The current laser has a pulse width worse than 300 ps. This is the main reason for the current level of single shot RMS (3-4 cm). The main task for the future is to modernize the system and improve the RMS up to 1 cm. To reach this goal the replacement of the laser by new equipment with a ~50 ps pulse width is planned. The next step is to replace the time interval counter and to increase the repetition rate from 300 Hz up to 600 Hz. These plans are expected to be implemented after 2020.

Station Personnel

The laser system at the observatory is maintained by the staff of operators, who work in shifts (two operators per shift). All operators are capable to carry out both VLBI and SLR observations even if they occur at the same time. The observation results are sent via network transmission to the processing center at IAA (Saint-Petersburg). There ,the data are processed and sent to EDC and other users. Repairs of the system and overall operation are conducted by the lead engineer Viktor Mitryaev.

The station operators are as follows:

- Andrey Shatilov
- Pavel Kisilev
- Victor Kononenko
- Militina Lysenkova
- Aleksander Ptitsin
- Nikolai Dzuba
- Galina Kravchenko
- Anastasiya Markelova
- Oleg Pervakov
- Nataliya Zabavskaya
- Evgeny Kvashnin

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Zimmerwald, Switzerland

Authors: *Emiliano Cordelli, Pierre Lauber, Thomas Schildknecht*
Responsible Agency: Astronomical Institute University of Bern (AIUB)

System: ZIML/7810
Location: Swiss Optical Ground Station and Geodynamics Observatory Zimmerwald, Waldhof 2-4, 3086 Zimmerwald, Switzerland
Latitude: 48.8772° N, Longitude: 7.4652° E, Elevation: 951.2m

Station Operations

A total of 3,942 passes, resulting in 54,625 normal points, and 661.82 hours of observations were acquired in 2016. In 2017, the performances increased to 11,038 passes, 141,705 normal points and 1618.1 hours, while in 2018 we reached 15,989 passes, 200,619 normal points and 1792.98 hours.

The poor performance in 2016 and in the beginning of 2017 was due to technical issues that started in December 2015 with the laser double pass amplifier failing, which was first repaired, then we were obliged to use it at lower gain (summer 2016), and finally needed to be replaced in February 2017.

Since March 2017, the station is running normally and the team is striving for the improvement of the station efficiency and measurement accuracy. The ZIMLAT telescope is shared during nighttime between SLR operations, didactical activities, space debris, and classical astronomical observations.

Figure 8-103. Swiss Optical Ground Station and Geodynamics Observatory Zimmerwald today.

System Improvements

In order to speed up the acquisition of difficult targets, like newly launched satellite, the SLR system has been equipped with a night-tracking camera. A first analysis after the camera integration has shown an improvement of the station efficiency. The camera, which is used for correcting the pointing of the telescope in real time, allows us to track LEO and MEO defunct satellites with poor predictions with our SLR system. The main outcomes of the tracking are the angular positions of the object in the sky (azimuth and elevation), its distance, and its brightness. All these measurements are acquired synchronously with the timing accuracy provided by the SLR system and can be used for both, the attitude, and the orbit determination of space debris.

In the frame of the European Laser Time Transfer (ELT) project, we carried out a calibration session together with the University of Prague. The calibration campaign has been performed in order to determine one-way calibration constants, which are relevant for this experiment being sensitive to one-way delays. Significant one-way internal system calibration delays can now be expressed by ELT calibration constants and can in future be determined more easily using simple reproducible experiments without external calibration efforts.

To achieve a highly stable local time and frequency, a maser has been installed.

To improve the UTC time scale precision from 100 ns to 15 ns, an additional GPS-receiver has been procured and integrated. The receiver is embedded into the station time system in such a way that the previously determined calibration constants should be preserved.

With the newly installed GPS-receiver and a time interval counter, the local time derived from the maser is now measured against UTC (GPS) with a precision of 1 ns instead of 30 ns. SLR measurements provided to the ILRS are now tagged with epochs at 15 ns precision.

Because the ZIMLAT SLR telescope optics are also prepared for infrared, it was possible to host a quantum mechanics experiment of the Institute of Applied Physics of the University Bern (IAP). The experiment uses an infrared CW laser to produce entangled photons and was setup at the station as a starting point for the use of entangled photons in free space. The photon source was installed in the coudé path and a retro reflector mounted at 659m distance from the telescope.

Current Challenges and Future Plans

The main challenges for the next two years are:

- SLR System/s: evaluation and replacement of the current 100Hz system with a kHz laser. At the same time, we should be able to shorten the laser pulse width by a factor of 6 to about 10ps, which should improve the single shot measurements accuracy. The kHz system will also improve the station performance in terms of number of observed passes. The existing dome of the SLR system will be replaced by a new one to improve the safety of operations.
- Evaluation and implementation of a space debris laser system.
- Develop and adapt the current laser observation software to be compatible with the new kHz and space debris laser systems.
- Tracking camera: implement an automated closed loop to steer the telescope using images acquired by the tracking camera; develop a tool to improve the ephemeris with the acquired measurements from the tracking camera; extend the use of the tracking camera to daytime.
- ELT experiment: adapt the current laser triggering software in order to consider the changing light travel time to the ISS.
- Quantum Mechanics experiment: perform coincidence tests at the telescope using the installed retroreflector. Extend this experiment to LEO satellites.

Station Personnel

List of station personnel and responsibilities:

- Prof. Dr. Thomas Schildknecht: Director of the Swiss Optical Ground Station and Geodynamics Observatory Zimmerwald and primary contact
- Dr. Elmar Brockmann (representative of Federal Office of Topography SwissTopo): Secondary contact
- Dr. Emiliano Cordelli: Research and development, substitute of director
- Dr. Pierre Lauber: Laser maintenance and electronics engineer
- Marcel Prohaska: Instruction and coordination of observers

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Section 9:

Standing Committee, Study Group, and Board Activities

Section 9: ILRS Standing Committee, Study Group, and Board Activities

Authors: *ILRS Standing Committee, Study Group, and Board Chairs and Co-chairs*
Editors: *Carey Noll, Michael Pearlman*

Introduction

The ILRS Governing Board established several standing committees (SCs) and study groups (SCs) to carry out the business of the ILRS. The SCs, formerly called ILRS Working Groups, address the continuously evolving tasks of the ILRS; study groups. are formed to work special investigations or tasks of a temporary nature. Currently, the ILRS has five SCs as shown in Table 9-1 below. These groups provide the expertise to make technical decisions and to plan programmatic courses of action and are responsible for reviewing and approving the content of technical and scientific information maintained by the Central Bureau.

Table 9-1. ILRS Standing Committees, Study Groups, and Boards

Standing Committee	Chair/Co-Chair
ASC Analysis Standing Committee	Chair: Erricos Pavlis Co-Chair: Cinzia Luceri
DFPSC Data Formats and Procedures Standing Committee	Chair: Christian Schwatke Co-Chair: Randy Rickleffs
MSC Missions Standing Committee	Chair: Toshi Otsubo (2016-2019) Co-Chair: Scott Wettzel (2016-2019) Chair: Stephen Merkowitz (2019-present) Co-Chair: Rob Sherwood (2019-present)
NESC Networks and Engineering Standing Committee	Chair: Matt Wilkinson Co-Chair: Georg Kirchner
TSC Transponder Standing Committee	Chair: Ulli Schreiber Co-Chair: Jean-Marie Torre
ILRS Study Groups	**Chair/Co-Chair**
Space Debris Study Group	Chair: Georg Kirchner Co-Chair: Daniel Kucharski
ILRS Boards	**Chair**
Quality Control Board	Michael Pearlman

Analysis Standing Committee (ASC)

Author: *Erricos Pavlis/JCET/UMBC, Cinzia Luceri/e-GEOS S.p.A.*

Chair: Erricos C. Pavlis
Co-Chair: Cinzia Luceri

Role of the Analysis Standing Committee

The ILRS is an official Technique Service in the International Association of Geodesy (IAG) and the International Earth Rotation and Reference Systems Service (IERS). To fully and systematically exploit the unique aspects of the SLR observations, the ILRS established the Analysis Standing Committee (ASC) to lead the development of official products, to monitor and qualify the performance of the tracking network, and to address various issues with the SLR data and products. Some of the main duties of the ASC include data quality control, the definition of the estimated parameters group for official data analyses, the selection of the satellite data to be used, the products format definition, the optimization of the underlying processes, and the development of an official combination product on the basis of the individual AC contributions. Additional products being considered are evaluated through a number of so-called pilot projects (PP), with several initiated during the past few years, some of them successfully completed and others still ongoing. This contribution to the ILRS 2016-2019 Report is a review of the main accomplishments during that period and an update on the status and the results of these efforts. General information on ASC activities, membership and more detailed information on the pilot projects can be found on the relevant pages in the ASC section of the ILRS website *https://ilrs.gsfc.nasa.gov/science/awg/index.html*.

Recent Achievements

Over the period covered in this report (2016-2019), the ILRS ASC met on six occasions. ASC meetings are usually planned to take place on dates close to major geophysical meetings (AGU/EGU) or other venues associated with ILRS events, in order both to maximize ASC members' attendance and to also encourage interaction with other scientists. The six occasions are listed below along with the dates and location:

- April 2016 - The 37th ASC meeting was held on April 22 at the TU Wien in Vienna, Austria.
- October 2016 - The 38th ASC meeting was held on October 8 in Potsdam, Germany.
- April 2017 - The 39th ASC meeting was held on April 22 at the TU Wien in Vienna, Austria.
- October 2017 - The 40th ASC meeting was held on October 1 at the University of Latvia in Riga.
- April 2018 - The 41st ASC meeting was held on April 12 at the TU Wien in Vienna, Austria.
- November 2018 - The 42nd ASC meeting was held on November 4 at the Mt. Stromlo Observatory complex in Canberra, Australia.
- April 2019 - The 43rd ASC meeting was held on April 6 at the TU Wien in Vienna, Austria
- October 2019 - The 44th ASC meeting was held on October 1 at the Paris Observatory in Paris, France

Detailed agendas and minutes of the deliberations at these meetings, along with the presentations from each of the participating groups, can be found online at the ASC activities and meeting section of the ILRS website (*https://ilrs.gsfc.nasa.gov/science/awg/awgActivities/index.html*). In addition to these meetings, the chairs and several members of the ASC participated with presentations and contributions to several position papers in the Unified Analysis Workshop of the Global Geodetic Observing System (GGOS) and IERS, in Paris, France, July 10-12, 2017 and October 02-04, 2019.

The prime activity of the ASC is to use the SLR data for the routine, frequent and consistent development of a unique, high-quality analysis product that is in high demand in the science community, e.g., station positions and daily EOP. The entire collection of these products contributes to the development of the ITRF model updates every 5-6 years, along with similar products from the other geometric IAG Services. An official analysis of a 7-day arc provides an estimate for station coordinates and daily EOPs, and it is generated by the ILRS Analysis Centers (ACs) and Combination Centers (CCs) on a daily basis, and submitted to the IERS as an official ILRS contribution. The 7-day arcs comprise data of high-quality laser range observations to LAGEOS, LAGEOS-2 and the two Etalon satellites, and the ILRS network is encouraged to support this valuable work, ideally by tracking these satellites day and night, seven days a week. Two different products are distributed each week: a loosely constrained estimation of coordinates and EOP and an EOP solution, derived from the previous product, fully constrained to the standard ITRF. The distribution of these products in the early days of the ILRS ASC was done on a weekly basis. However, starting in May 2012 the official "position + EOP" product is delivered daily, with the starting day of the 7-day arc shifted forward daily by one day. This was deemed necessary to ensure that our customer USNO, hosting the IERS Rapid Prediction Center would have access to the most fresh SLR-derived EOP possible. The ASC launched an additional official product during the reporting period, starting the weekly distribution of precise orbits for the four satellites used in the development of the official pos+EOP products. The orbits are delivered as 7-day SP3c-formatted files in the standard ITRF frame.

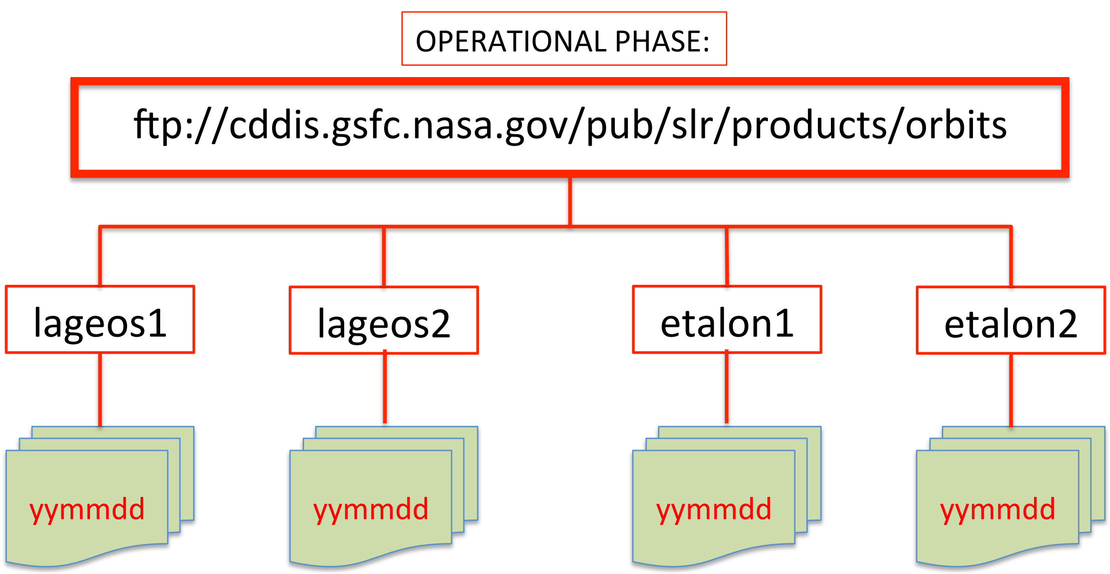

Figure 9-1: Archive structure of the weekly submissions of official ILRS Orbit products at the CDDIS DC (similarly at EDC DC).

In addition to the operational products development, the ASC contributed in the evaluation of the ITRF2014P (preliminary) and ITRF2014 (final) models. Upon release of the final model the ASC planned and executed the implementation of the new model for all ILRS applications. Due to the delayed release of the associated EOP series from IERS, the use of the new model in the official products was only possible in mid-2017. During the reporting period, eight different ACs supported the operational activities providing products routinely: ASI, BKG, DGFI, ESA, GFZ, GRGS, JCET and NSGF. Unfortunately, GRGS stopped delivering its contributions in mid-2016 and after they were given several extensions to recover from their processing system breakdown, they were finally placed in the AAC group until they can demonstrate again a sustained contribution to the official products. Two CCs are routinely delivering the combined products: ASI (primary ILRS-A) and JCET (backup ILRS-B).

In 2016 we had the first results from the Pilot Project (PP) Station Systematic Error Modeling—SSEM, with a very good agreement amongst the individual contributions from each AC for the adopted test period of analysis (2005-2008). This provided a verification that the new approach works as expected through the examination of recovered biases at stations with known issues which had been corrected using engineering measurements, e.g., at Matera (7941) around the middle of 2007 and at Herstmonceux (7840) prior to 2007 (Figure 9-2).

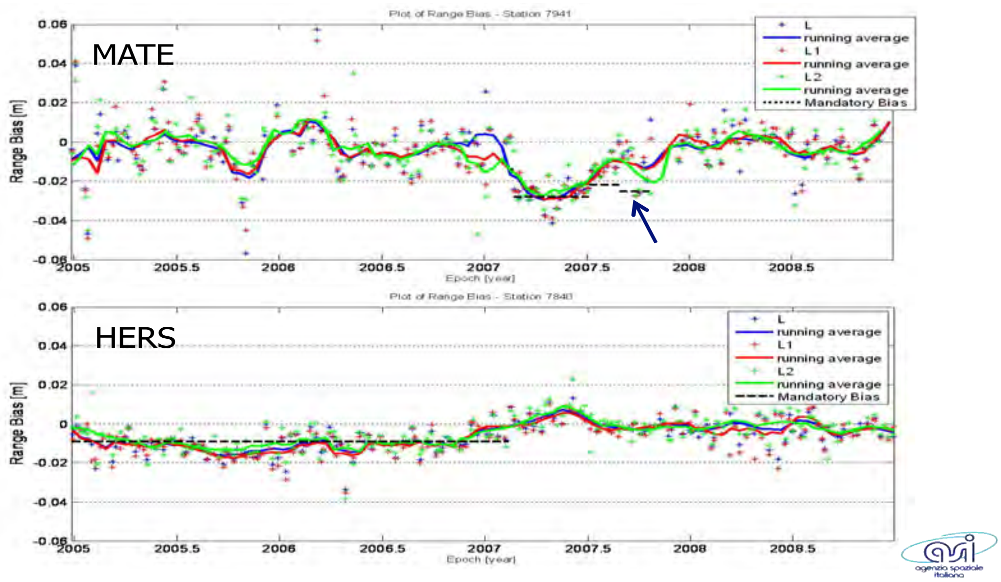

Figure 9-2: Weekly adjusted range biases to LAGEOS and LAGEOS-2 (red and green crosses respectively) at two SLR sites with (independently) well-established estimates (dashed lines).

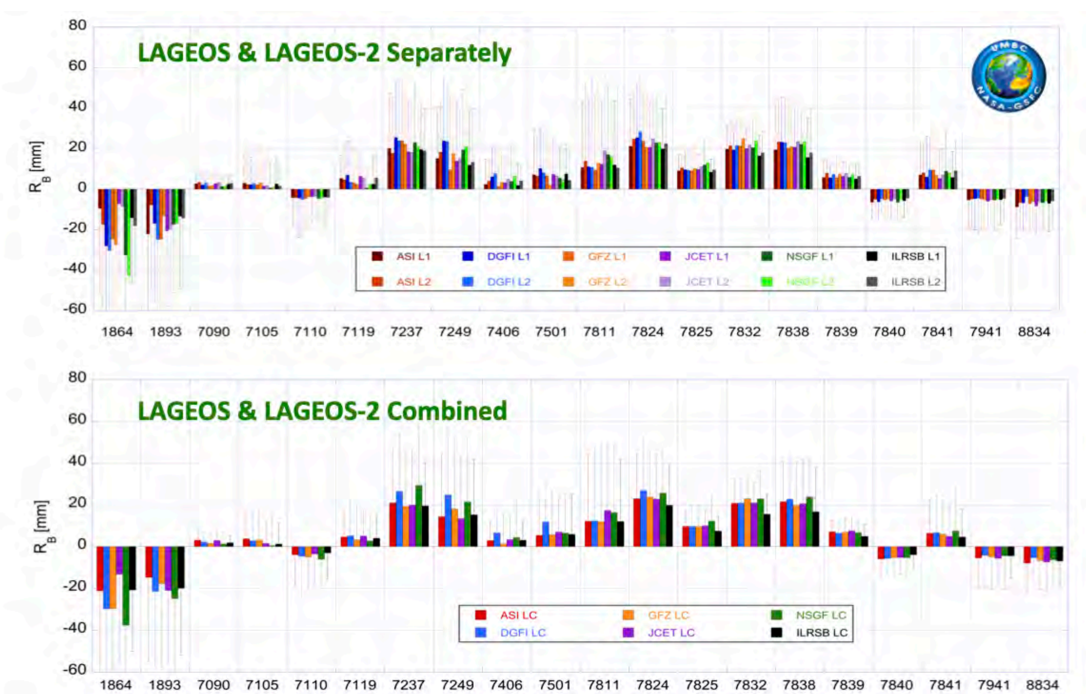

Figure 9-3: Long-term range biases averaged over the test period 2005-2008, estimated separately (top) for LAGEOS and LAGEOS-2 and in combination (bottom), at twenty SLR sites, and from the five participating ACs and the ILRS-B combination (back-up). There is excellent agreement amongst ACs, especially for the stronger, higher yield systems.

The initial approach compared the independent estimation of biases for each of the two LAGEOS and in combination, with the ASC subsequently deciding that due to small but observable differences between the two targets, the estimation of separate biases was deemed more appropriate (Figure 9-3).

The preponderance of significant biases was observed to be positive (Figure 9-3) and when the tests included the Etalon satellites, there was a clear systematic difference between the two targets for nearly all systems (Figure 9-4). This was a clear indication that there were shortcomings with our "target signature" model, the CoG correction for the ranges from each system. By the end of 2016 the SSEM PP had already created great interest due to these findings and the effect of these changes on the official ILRS products was the next task ILRS turned to.

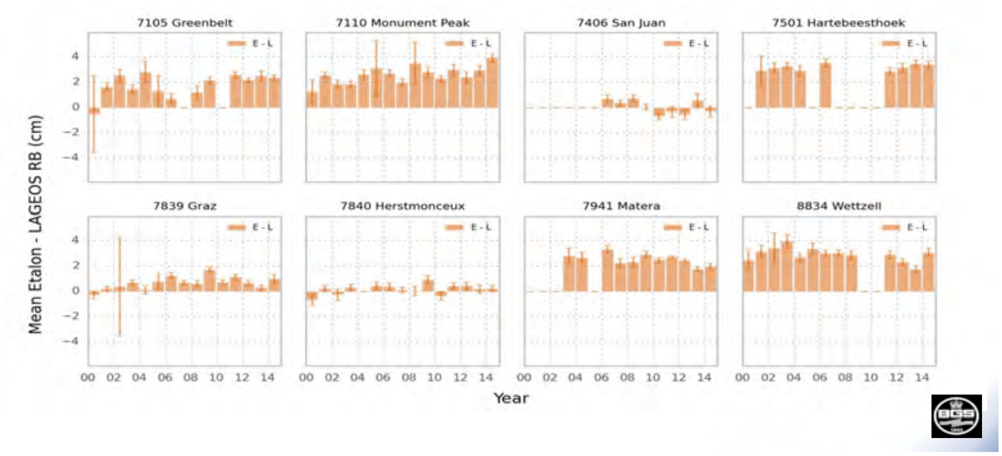

Figure 9-4: Long-term yearly averaged range bias differences Etalon-LAGEOS over the period 2000-2014, at eight SLR sites with very diverse equipment. The fact that some of the best systems showed few-millimeter level LAGEOS biases led to the conclusion that these large differences emanated from the CoG model for the two Etalons.

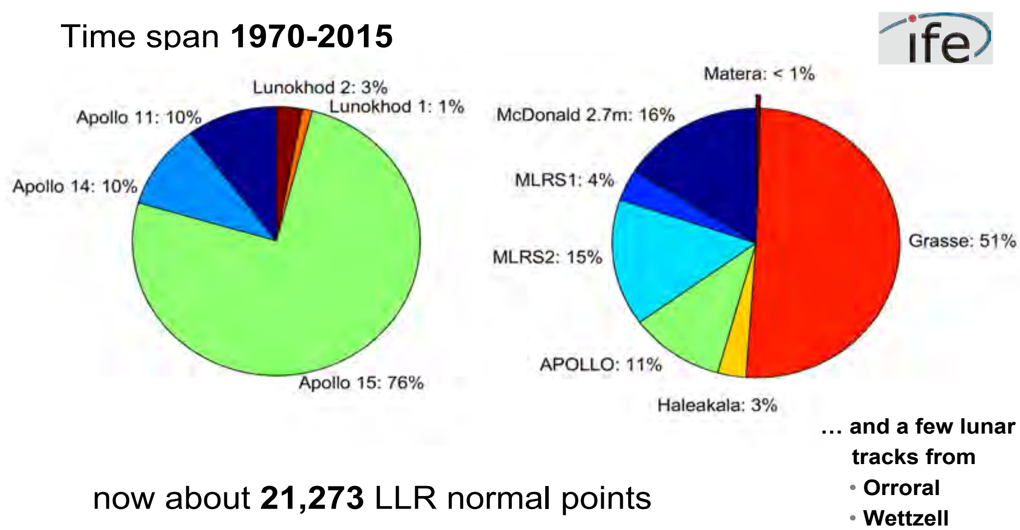

Figure 9-5: LLR NP collected over 1970 - 2015 in terms of their distribution by lunar array and by ground system. The Apollo 15 array and the Grasse station are the most significant contributors in the two categories respectively.

Along with the exciting SLR activities, the LLR group showed increased observations from most of the LLR-capable sites and a steady increase of the yearly accumulated data from all lunar targets, but the majority (>75%) still coming from the large Apollo 15 array and more than half contributed by Grasse (Figure 9-5).

In early 2017, initial tests at NERC showed that the application of the detected biases in the reanalysis would eliminate a large portion of the scale difference between the SLR-based TRF with the current

ITRF2014 (Figure 9-6). The fact that the new approach seemed to imply that biases could remove a great percentage of the scale difference between SLR and VLBI TRF realizations fueled the community that embarked on the completion of the SSEM PP with much more increased urgency, looking forward to the upcoming milestone, the ITRF2020 effort.

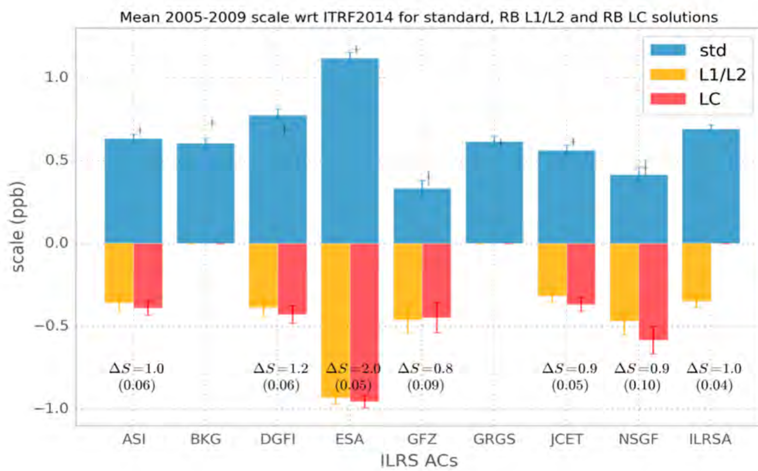

Figure 9-6: Scale differences between ITRF2014 and the standard analysis products by AC/CC over the test period 2005-2009, and between ITRF2014 and two test cases, one with the adjustment of separate LAGEOS range biases and one in combination. On average a ≈1 ppb difference between the two approaches is seen.

Table 9-2: Distribution of attributes of SLR data passes for the main ITRF-supporting targets over the period 2007-2017. Pass duration is in minutes, angles are in degrees [°].

LAGEOS	Pass Duration	Acquisition Elevation	LOS Elevation	Maximum Elevation
Minimum	0	-84.5	-83.9	0
Maximum	99	89.7	89.6	89.65
Points	89582	89582	89582	89582
Median	13	35.2	32.9	49.48
Std Deviation	12.17	15.52	16.61	17.84

LAGEOS-2	Pass Duration	Acquisition Elevation	LOS Elevation	Maximum Elevation
Minimum	0	-88.7	-85.9	0
Maximum	87	89.3	89.5	89.9
Points	79052	79052	79052	79052
Median	14	38.9	38.1	56.0
Std Deviation	13.69	16.67	17.96	18.00

LARES	Pass Duration	Acquisition Elevation	LOS Elevation	Maximum Elevation
Minimum	0	-89.5	-87.6	0
Maximum	23	88.5	88.1	89.4
Points	36485	36485	36485	36485
Median	5	28.0	25.8	43.3
Std Deviation	3.69	14.40	15.58	18.97

As the preparations towards the ITRF2020 reanalysis effort were initiated, several ACs looked into different modeling aspects where inconsistencies amongst techniques larked and could cause systematic differences at the combination step. Questions about the necessity to expand our refraction model were raised, however, a review of the collected data set indicates that the majority of the collected data were mostly taken at elevations ≥ 20° (Table 9-2), therefore the current model is sufficient for sub-mm accuracy.

At this point we set two goals to be completed well before we would start the reanalysis process for ITRF2020:

- The recalculation of the CoG correction model at least for the four targets used for TRF development and LARES (since it would be included in ITRF2020), and
- The re-evaluation of the SSEM series over the entire period 1993-present, using the new CoG model, so that a reference set of biases would be available for the reanalysis.

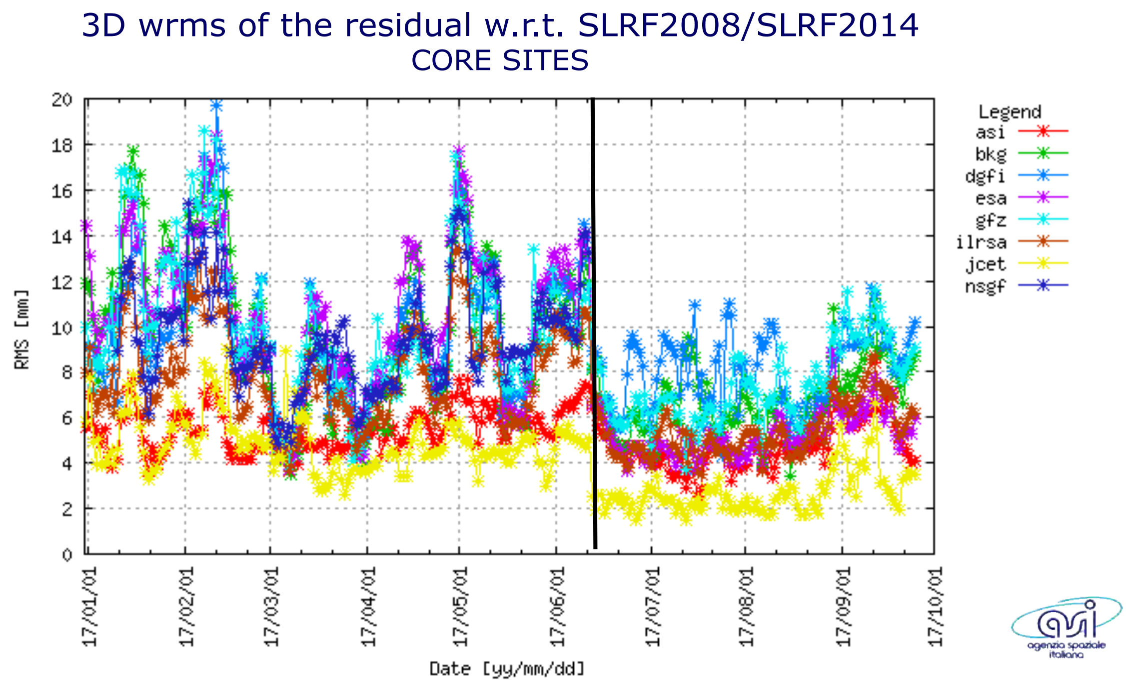

Figure 9-7: 3D WRMS of the residuals of ILRS AC/CC series for Core sites after transformation to SLRF2008 and SLRF2014. After the adoption of SLRF2014 in mid-2017 we can see a significant drop in WRMS for all AC/CC contributing to the comparison.

By the middle of 2017 the IERS released the official EOP series that is consistent with the ITRF2014 and the ASC switched from SLRF2008 to the new version SLRF2014, based on ITRF2014. The adoption of the new model resulted in a very significant improvement of the ASC products (Figure 9-7).

An important model that became also an issue was the consistent adoption of the Mean Pole across all geometric techniques and for all applications. In 2016 it was noticed that the online file of IERS had been changed several times without prior announcement and with no record of how many such changes had taken place and when. On three such occasions the file was downloaded, and the results were compared, indicating large discrepancies over the main period of interest (indicated by the red arrow in Figure 9-8).

To avoid inconsistencies, IERS replaced the tabular series with a FORTRAN routine (*IERS_CMP_2015.f*) that provides the CMP coordinates for a given date. Since the routine was not updated for use during our period of interest, the ILRS ASC created a clone routine (*ILRS_CMP_2016.f*) that included a projected forecast of the CMP for a few years, so that the analysis of current data could proceed.

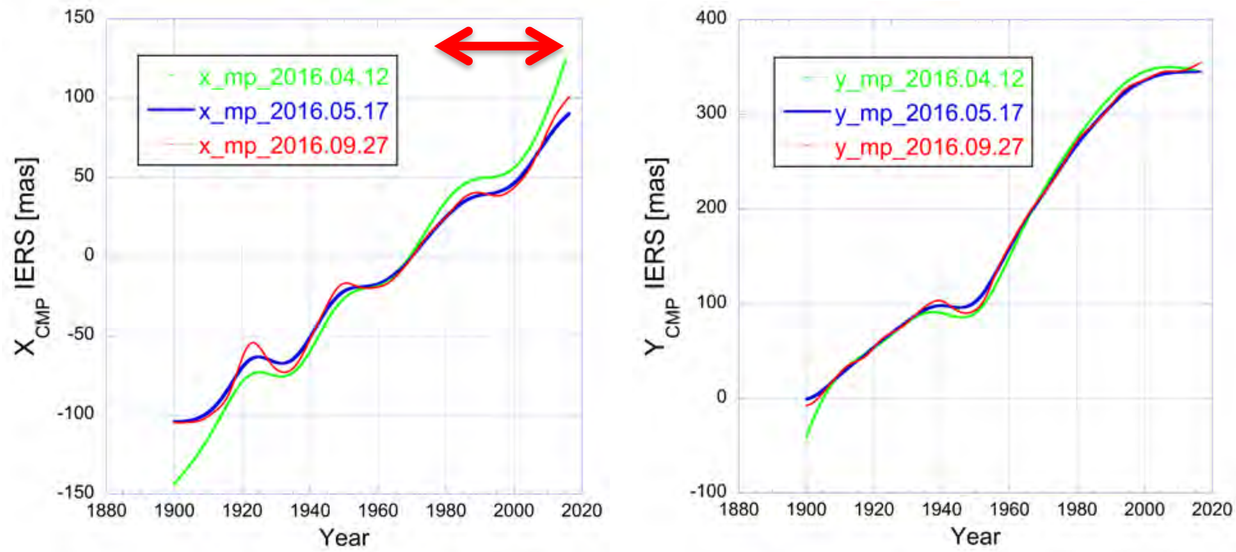

Figure 9-8: Conventional Mean Pole coordinate series downloaded from the IERS web site on three different dates. Over some periods the differences reach 30-50 mas, well above the ±10 mas quoted accuracy.

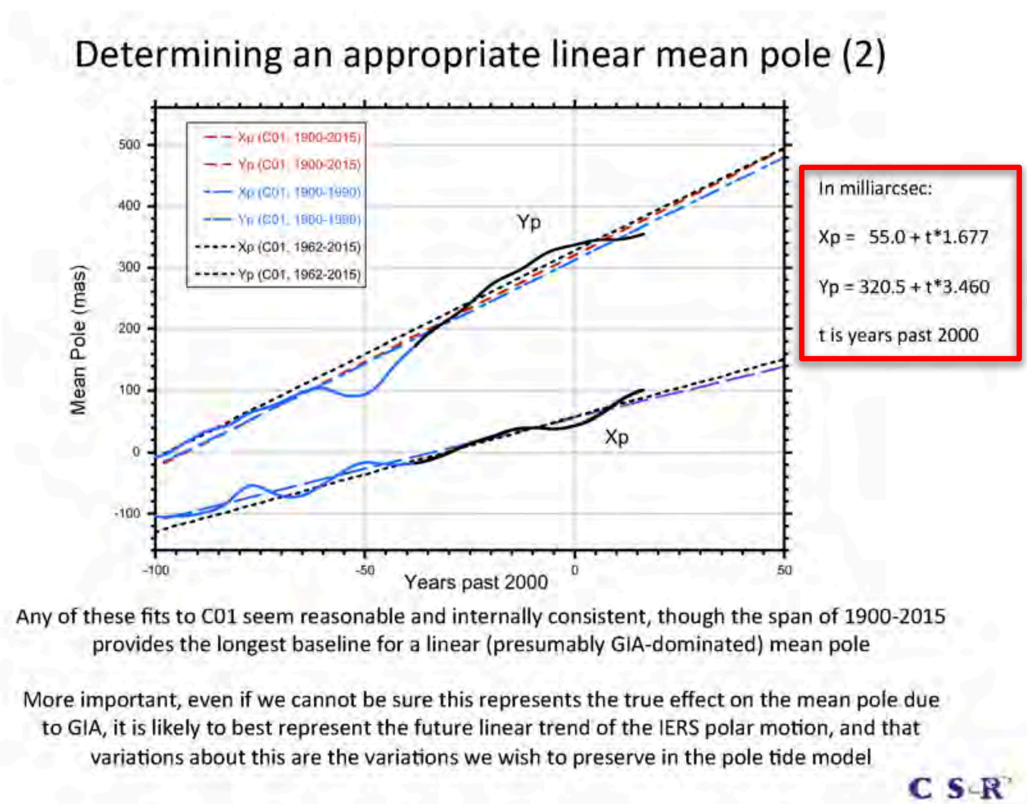

Figure 9-9: Linear fits to IERS C01 series for the development of a linear mean pole model that would replace the CMP. Fitting on subsets of the C01 series resulted in insignificant differences, in the red box the adopted model and parameters.

The lack of a coordinated approach from IERS generated heated discussions in the geometric technique community and eventually, a dedicated session during the 2017 UAW meeting examined the issue and its implications, especially in what concerns the relationship with the degree-2, order-1 gravitational harmonics, and a consensus model was agreed and proposed to IERS. The IERS Directing Board adopted the simple linear model during the Fall 2017 AGU meeting and the appropriate renaming of the CMP to "linear mean pole" to avoid misinterpretations. The actual numerical model was computed and provided to the IERS by the CSR/UT AAC (Figure 9-9), that was instrumental in clearing the confusion associated with this topic for several years.

An important additional resource in tracking and correcting systematic errors in SLR data was added to our arsenal in 2017. The use of the T2L2 experiment products based on FR SLR tracking data from the ILRS network to Jason-2, the oceanographic mission that carried the required instrumentation. Most SLR stations do show significant systematics in their time-keeping record, and even though there is a directive to keep these within ±100 ns from official UTC, this is not easily maintained and sometimes the stations are way outside the limits without even knowing it (Figure 9-10).

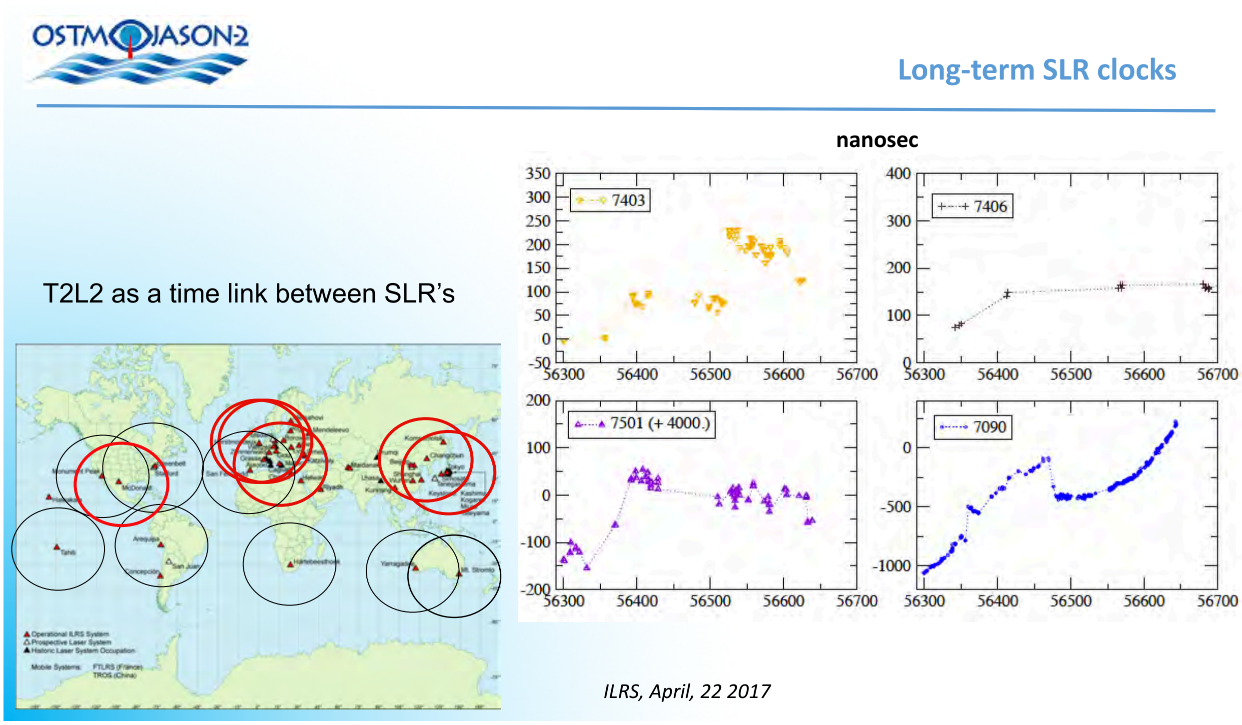

Figure 9-10: Example time series of SLR station clocks records derived from T2L2 comparisons; in some cases (e.g., 7501) the actual time bias is orders of magnitude outside the official ±100 ns limits.

A complete set of time biases for the period 2008-2017 were provided to the ASC and adopted for application in the next reanalysis and all future ones, after an examination of the series to identify the significant ones for ITRF support. The complete set is included in the Data Handling file and the ones recommended for application in the production of the official ILRS products are clearly indicated in the file.

In 2017 the ILRS accepted a new AAC hosted by the Wrocław University of Environmental and Life Sciences with a focus on processing SLR data to GNSS satellite targets. The new AAC demonstrated the contents and use of an online web service (Figure 9-11), capable of providing information related to the data they analyze, for years past, present and promised to maintain it in the years to come.

As we entered 2018, the ASC had decided to repeat the SSEM analysis with the final accepted standards, estimating a separate bias for the two LAGEOS and a combined one for the two Etalons, using the new linear mean pole and an updated version of the CoG tables released on 2017.03.29. The series obtained from this reanalysis were used to initiate the identification, on a site by site case, the periods when that site exhibited a significant, detectable bias, and the adoption of a mean value with an appropriate error-bar as a forward model of the bias in the upcoming ITRF2020 reanalysis (Figure 9-12).

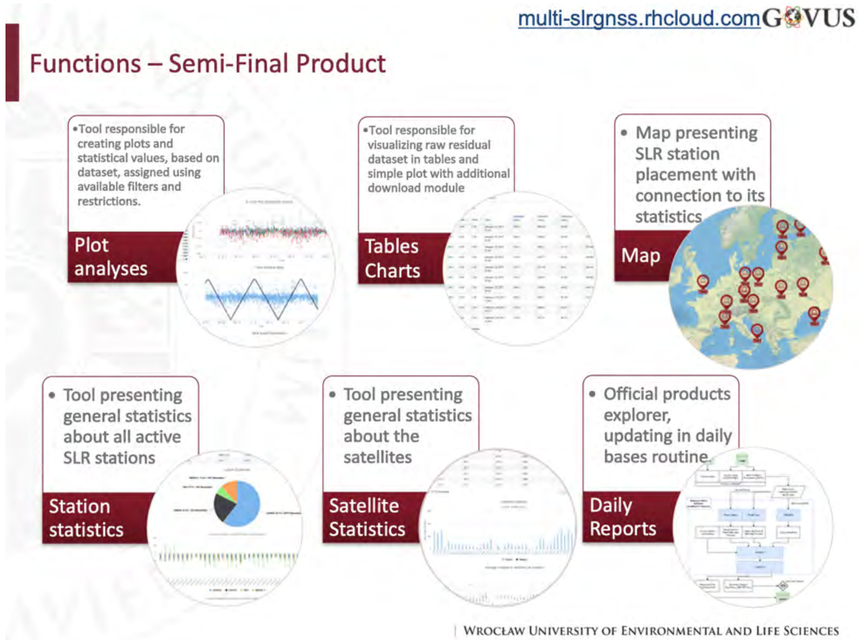

Figure 9-11 : An overview of the available online services from the newly accepted Wrocław University of Environmental and Life Sciences AAC GOVUS site and the link to access it.

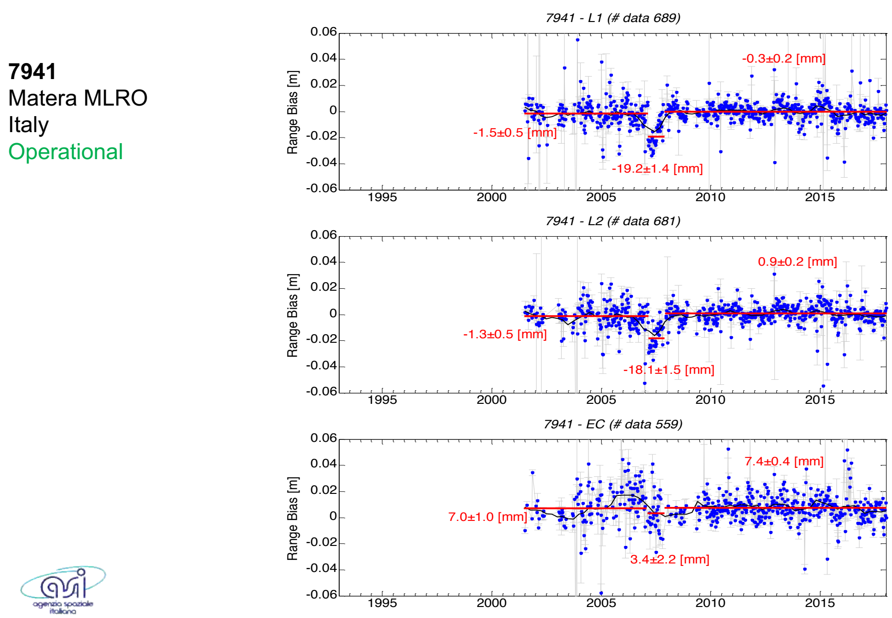

Figure 9-12 : An example with Matera's MLRO (7941) Range Bias series, identifying periods of significant and persistent range biases, and computing their mean and standard deviation for use in forward modeling in future reanalysis.

The application of such biases and reanalysis of the SLR time series of weekly products indicated very clearly that the new approach would result in the change of the scale with respect to the standard approach by about 1 ppb (!) as it is clearly seen in the comparison below (Figure 9-13).

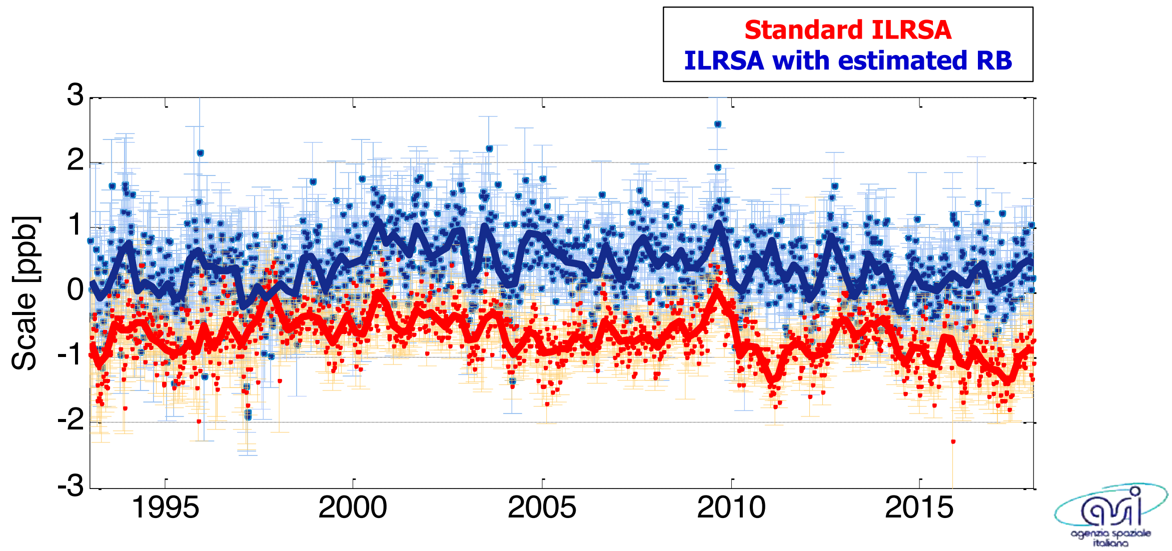

Figure 9-13 : Preliminary results from the comparison of the two ILRS-A weekly series (1993-2017) in terms of scale differences, indicating the significant and systematic scale change between the two approaches of data reduction.

The long-term biases that were obtained from the recent reanalysis (Figure 9-14) indicated that the core network was only affected at the ±10 mm level, however, it became obvious that these biases were not the result of undocumented problems at the stations alone, since they were distributed in a very lopsided fashion, being mostly positive throughout the network. This pointed to a source that is common to all systems and all targets, the applied CoG correction model.

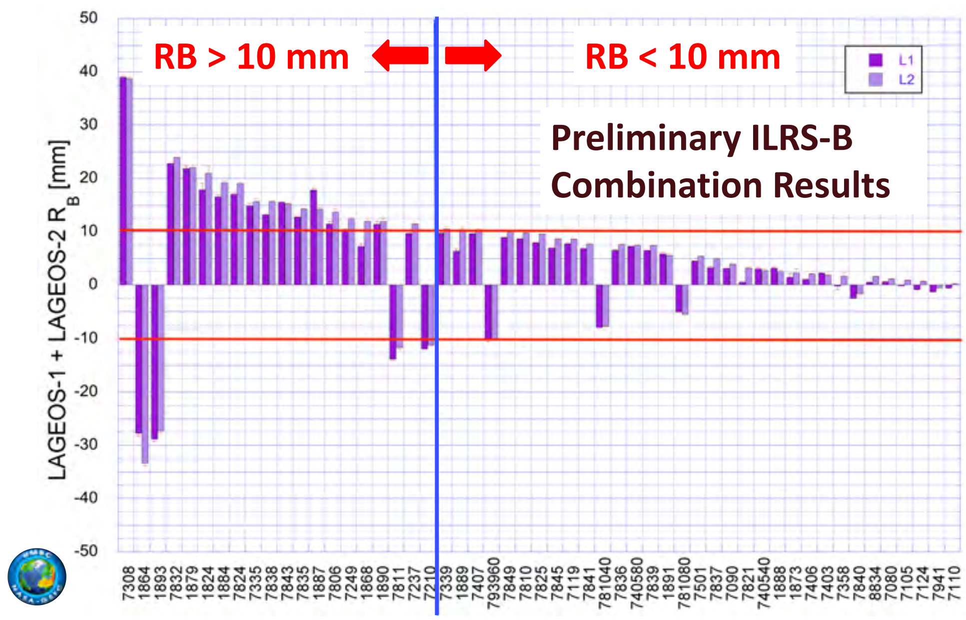

Figure 9-14 : The long-term biases obtained from the reanalysis of the ILRS-B weekly series (1993-2017) for LAGEOS and LAGEOS-2. The majority of the core sites show R_b within ±10 mm and the consistent but small difference between the two targets is clear.

Near the end of 2018 the new, revised CoG model from NERC is about to be released and preliminary results are presented at the Canberra Workshop, where the application of the revised model results in large changes for the Etalon CoG model for almost all stations while the change of the model for the two

LAGEOS results in mm-level individual station bias changes and a more random distribution of the reduced relative (LAGEOS – LAGEOS-2) R_b differences over the network (Figure 9-15).

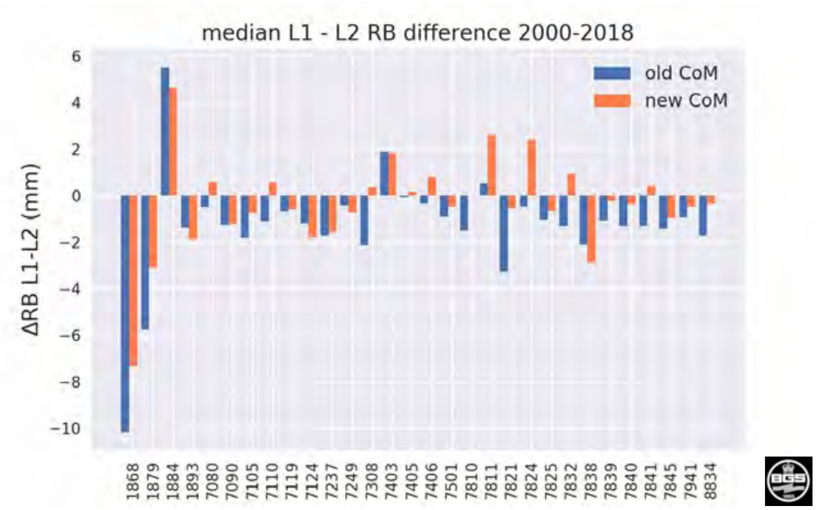

Figure 9-15 : The application of the revised CoG model from NERC resulted in smaller long-term range biases and a more random distribution of the median difference between the two targets LAGEOS and LAGEOS-2 (2000-2018).

In 2018, a discussion between the JCET and DGFI teams for the possible introduction of a new ILRS product based on SLR tracking data to GNSS and other targets creates interest for a closer examination of the existing archived data. The group from ESA, with a long history in GNSS data analysis and applications, presented preliminary results comparing the standard ASC products to possible future combinations with GNSS data (Figure 9-16). Although there is general agreement at the few millimeter level, there are also very clear cases with very significant differences that are clearly the effect of the GNSS contributed data. It is comforting to see that with some additional effort, we could easily reach a level of agreement and a new product would be possible in the near future.

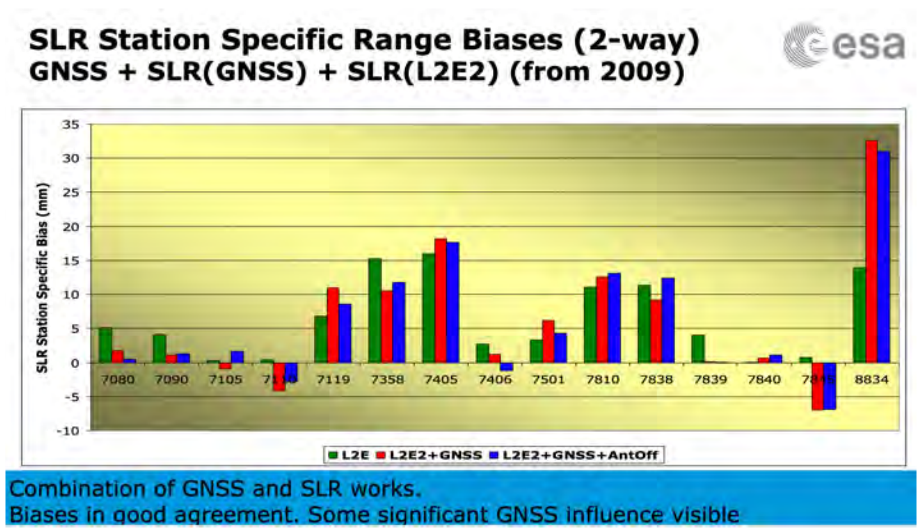

Figure 9-16 : Annual (2009) mean range biases obtained from the standard ASC analysis compared to those obtained from the addition of SLR data to GNSS targets (including tests with antenna offset calibration).

The Lunar AAC hosted by IAA introduced the work that is taking place in their institution and some of the services they provide to the LLR community (Figure 9-17). An eventual joint SLR-LLR solution has always been in the plans, however, it is only at this point that this seems to have a real chance of happening soon.

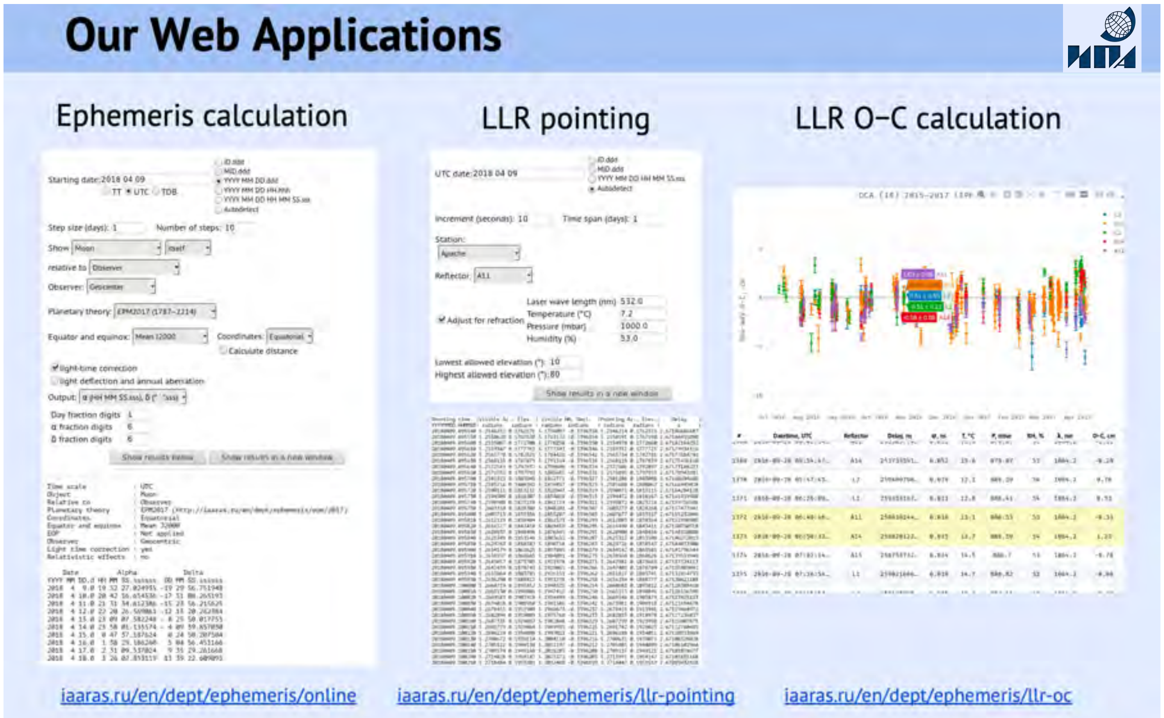

Figure 9-17 : A sample of services and results provided to the LLR community by the IAA/RAS LAAC.

The Shanghai Astronomical Observatory (SHAO) AAC presented work that compared the estimation of atmospheric delay horizontal gradients from GNSS data and SLR data, the results however did not cover the global network neither a large enough period of time. Additionally, the magnitude of the effects seemed a lot smaller than previous works had indicated and it was decided not to extend our efforts at this time given that these effects showed less than 1 mm RMS signature.

At the 2019 IUGG the Wrocław AAC presented an empirical model of horizontal gradient corrections for application to SLR observations. Their model is based on the analysis of eleven years of numerical weather data at each SLR station with a 6-*hr* temporal resolution. The model was applied for evaluation on a limited data set spanning a few years of official ILRS products, with mixed results and very small effect overall. Its application therefore has been postponed for the future, after further improvement in its resolution and accuracy has been achieved. Its application on data from for low-orbiting satellites, such as LARES, Starlette and active LEOs may be especially advantageous.

Unfortunately, lack of a final CoG model well before the end of 2019 prohibited us from finalizing the SSEM PP in time for this report, although the preliminary results on the basis of the provisional model releases were very encouraging. There were no results from the PP related to the introduction of LARES as a fifth target in support of the ITRF development either, therefore, its launch was postponed for after completion of the SSEM PP.

Current Activities

At the time this quadrennial report is compiled (May 2020), we have reached and surpassed several milestones set over the past year. The final CoG model was delivered by NERC in November 2019 and after some minor adjustments and additions, it has been placed in use. The ASC has adopted that model for all products and applications. We are in the process of revising the ILRS web pages where this will be presented and archived, including past and future versions.

A final reanalysis for the SSEM PP series has been completed and the SINEX collection is now in the process of forming a combination. Once this step is completed the individual series of range biases for each site will be examined and the periods of persistent range biases identified, followed by the computation of the mean bias for each period and its standard error. The ensemble of these series of mean biases and associated epochs of validity will comprise the model for range biases which will become part of the new Data Handling file and the basis for the ITRF2020 reanalysis effort.

An IERS Study Group on High Frequency EOP (HFEOP) completed its testing and ILRS had several participations that supported the testing of a large number of candidate models to replace the outdated model in the IERS Conventions. After careful considerations the IERS adopted the model of Desai and Sibois which is now the one in use by the ILRS ASC. The results from different models were very close as one can see in Table 9-3 which summarizes the tests of all of the submitted models at JCET AC.

Table 9-3: Results of tests performed at JCET for all HFEOP candidate models over 2017. The models are evaluated in terms of their EOP components bias w.r.t. the components of IERS C04 and the scatter about it. The selected/adopted model in the red box.

Model	Libration Not Included						Libration Included					
	Xp_J - IERS C04		Yp_J - IERS C04		LOD_J - IERS C04		Xp_J - IERS C04		Yp_J - IERS C04		LOD_J - IERS C04	
	Mean [µas]	Std Deviation [µas]	Mean [µas]	Std Deviation [µas]	Mean [µs]	Std Deviation [µs]	Mean [µas]	Std Deviation [µas]	Mean [µas]	Std Deviation [µas]	Mean [µs]	Std Deviation [µs]
NONE	82.56	299.08	-18.05	313.03	-10.20	81.24	---	---	---	---	---	---
GSFC-IERS_2018	17.65	183.97	39.64	178.34	3.81	38.21	---	---	---	---	---	---
DESAI	15.19	184.19	38.50	178.54	4.55	38.34	15.67	184.31	38.73	178.05	3.92	38.04
EOT11A	15.39	184.16	39.98	179.26	5.10	38.38	15.27	184.26	39.28	178.82	4.58	38.13
FES2012	16.01	183.79	38.66	178.49	4.66	38.17	16.30	184.00	38.84	178.00	4.03	37.93
HAMTIDE	14.77	184.43	38.53	179.21	4.53	38.99	15.05	184.61	38.63	178.89	3.90	38.68
IERS2010	16.96	183.78	38.39	178.08	3.68	38.06	18.08	184.12	40.69	177.81	3.01	37.81
MAZDAK	15.12	184.26	38.73	178.13	4.93	38.33	15.51	184.42	39.02	177.70	4.31	38.05
VLBI	15.74	184.48	39.46	177.51	4.17	38.05	17.65	183.97	39.64	178.34	3.81	38.21
VLBI+GPS	16.54	184.07	39.09	177.54	3.05	38.08	17.58	184.31	39.33	177.45	2.45	37.88
GIPSON PM & VLBI+GPS UT1	---	---	---	---	---	---	18.22	184.32	39.07	177.18	2.50	37.89
GIPSON	---	---	---	---	---	---	14.96	184.42	38.61	177.46	4.08	38.18
GIPSON-L	14.05	184.35	38.24	178.07	4.74	38.35	14.98	184.41	38.64	177.48	4.05	38.19

During 2019 the ASC adopted a new standard for the SINEX format content to be used with the release of the reprocessed products for ITRF2020. This refers to the full disclosure and documentation of the Range biases, Time biases and CoG corrections applied to each participating station's data which are included in the process of generating the specific SINEX. In doing so, the information is immediately available to any user of the SINEX without the need to resort to looking up separate files, whether online or else. This also allows for a check of what the individual ACs have applied during their analysis, and the detection of errors and discrepancies. The format adopted for these three separate blocks to be included in the SINEX files was adopted during the ASC meeting prior to the 2019 UAW meeting in Paris. An example of what these will look like is shown in Figure 9-18.

```
*        1         2         3         4         5         6         7         8
*23456789012345678901234567890123456789012345678901234567890123456789012345678901234567890
*-------------------------------------------------------------------------------
+MODEL/RANGE_BIAS
*SITE PT SOLN T START_DATE__ END_DATE____ M RANGE_BIAS STD_DEV UNIT
 1873 51  501 L 08:288:00000 08:295:00000 R    -0.0193   1.000    m
 7810 51  501 L 08:288:00000 08:290:54321 R     0.0173   1.000    m
 7810 51  501 L 08:290:54321 08:295:00000 R     0.0183   1.000    m
 7810 60  501 L 08:288:00000 08:295:00000 R     0.0163   1.000    m
-MODEL/RANGE_BIAS

*        1         2         3         4         5         6         7         8
*23456789012345678901234567890123456789012345678901234567890123456789012345678901234567890
*-------------------------------------------------------------------------------
+MODEL/TIME_BIAS
*SITE PT UNIT T START_DATE__ END_DATE____ M __E-VALUE___ STD_DEV _E-RATE__ CMNTS
 1824 -- us   A 02:084:68460 12:085:00000 T      -24.400   5.000    0.0000 -----
 1873 -- us   A 07:059:00000 09:110:00000 T      -21.750  50.000   -0.2600 drift
-MODEL/TIME_BIAS

*        1         2         3         4         5         6         7         8
*23456789012345678901234567890123456789012345678901234567890123456789012345678901234567890
*-------------------------------------------------------------------------------
+MODEL/TARGET_SIGNATURE_GEOMETRY
*SITE PT SOLN T START_DATE__ END_DATE____ M   COM_CORR STD_DEV UNIT
 1873 51  501 L 08:288:00000 08:295:00000 C     0.1234   2.000    m
 1879 52  501 L 08:288:00000 08:295:00000 C     0.1234   2.000    m
 7810 52  501 L 08:288:00000 08:295:00000 C     0.0183   2.000    m
 7810 60  501 L 08:288:00000 08:295:00000 C     0.0163   2.000    m
-MODEL/TARGET_SIGNATURE_GEOMETRY
```

Figure 9-18 : An example of the format adopted for the three new Blocks in the ILRS SINEX format, for reporting corrections pre-applied to the data.

Some of the goals for the work to be done in the near future are summarized in:

- Estimation of low-degree SH of the gravity field
- Inclusion of LARES as a 5^{th} satellite in our operational product development
- Plan for the expansion of the target used in operational products
- Pilot project on NT Atm. Loading and Gravity

The overarching effort is of course the completion and submission of the reanalyzed data set for the development of ITRF2020, however, to achieve this some of the listed topics must be fulfilled first (LARES test) and some of the rest are long overdue (e.g., the low-degree SH product).

One of the most important achievements of 2019 was the completion and publication of the Special Issue of Journal of Geodesy on Laser Ranging, with leading guest editors the two ASC co-chairs. A list of the diversely themed articles included in the SI is shown in Table 9-4. Completion of the SI after a three-year effort was the result of the contributions from the entire ILRS community and provides a reference to the current state of the ILRS as well as a source for information of how we arrived at this point.

Future Plans

The work planned for 2020-2021 is predetermined by the fact that we are in the process of developing a new ITRF model, due for release sometime in late 2021. In the present year we will complete all of the reanalysis of the SLR data from 1983 to present and form combinations of the available weeks before the end of the year. In early 2021 we will complete these steps for the last few weeks of 2020 and a complete set of combined SINEXs should be ready for delivery to ITRS in February 2021.

Table 9-4: Articles included in the Special Issue of Journal of Geodesy on Laser Ranging

- *Preface to the second Special Issue on Laser Ranging*
- The ILRS: Approaching twenty years and planning for the future
- Geodetic Satellites: A High Accuracy Positioning Tool
- Lunar Laser Ranging - A Tool for General Relativity, Lunar Geophysics and Earth Science
- Information Resources Supporting Scientific Research for the International Laser Ranging Service
- The Next Generation of Satellite Laser Ranging Systems
- NASA's Satellite Laser Ranging Systems for the 21st Century
- Modernizing and Expanding the NASA Space Geodesy Network to Meet Future Geodetic Requirements
- Future SLR station networks in the framework of simulated multi-technique terrestrial reference frames
- Impact of network constraining on the terrestrial reference frame realization based on SLR observations to LAGEOS
- Satellite Laser Ranging to Low Earth Orbiters - Orbit and Network Validation
- Rapid Response Quality Control Service for the Laser Ranging Tracking Network
- Transitioning the NASA SLR network to Event Timing Mode for reduced systematics, improved stability and precision
- Systematic errors in SLR Data and their impact on the ILRS products
- Time Bias Service: Analysis and Monitoring of Satellite Orbit Prediction Quality
- Operating two SLR Systems at the Geodetic Observatory Wettzell - from local survey to space ties
- Time and laser ranging: A window of opportunity for geodesy, navigation and metrology
- Laser and Radio Tracking for Planetary Science Missions - A Comparison
- Assessment of the impact of one-way laser ranging on orbit determination of the Lunar Reconnaissance Orbiter
- Version of a glass retroreflector satellite with a sub-millimeter "target error"
- Studies on the materials of LARES 2 satellite

JOGE Vol. 93, #11,
Twenty articles and the preface, 287 pages

The remainder of 2021 will be devoted to tests and support of the ITRS Combination Centers, addressing any errors or inconsistencies that they might find in our submissions, and when the final ITRF2020 is released, the performance of tests for the evaluation of the new model with SLR data. Although these will be our main activities, we will in parallel address the other topics of the future goals and have not been completed by then. In particular, the generation of the new products of low-degree SH and products that take advantage of the SLR tracking of GNSS and other SLR targets.

Contact

 

Figure 9-19. ASC Chair Erricos Pavlis and Co-Chair Cinzia Luceri.

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Data Formats and Procedures Standing Committee (DFPSC)

Authors: *Christian Schwatke/DGFI-TUM, Randall Ricklefs/CSR*

Chair: Christian Schwatke
Co-Chair: Randall Ricklefs

Role of the Data Formats and Procedures Standing Committee

The Data Formats and Procedures Standing Committee (DFPSC) is responsible for developing standard procedures which affect the generation of full-rate and normal point data, maximizing the efficiency of the process of generating the laser data, and ensuring that data products contain all the information needed by the analysts

Recent Achievements and Current Activities

New CRD and CPF Formats

The update to the existing Consolidated Laser Ranging Data format (CRD) and Consolidated Prediction Format (CPF) was a major topic in previous years but is still an ongoing topic as the initial format released in 2009 requires upgrades to properly handle new applications. The formats must be updated for the following reasons:

- Additional information for the European Laser Timing (ELT) Experiment will be included in the prediction format;
- Debris tracking will be included to avoid multiple branches of the CRD format; and
- Additional information is included for meteorology, software, camera, calibration, predictions, etc.

For this task, a new study group, “Data Format Update”, was initiated, working on the update of the existing CRD and CPF specification, which was finally released in 2018. Since then, operation centers, data centers, stations, prediction providers, analysis centers, etc. have been encouraged to implement the new CRD and CPF specification.

Data Harmonization between OCs and Quality Assessment for CRD

The ILRS operates two global data and operation centers. In order to achieve homogeneous data validation, the applied quality checks by the OCs must be identical. Using the updated processes, the OCs check not only the data format but also performs analysis of the content of the fields. The DFPSC and the NESC have worked together in order to define reliable boundaries for all fields. The new data screening procedures were implemented at the OCs on August 15, 2019.

Station History Logs and Site Logs

The DFPSC worked on the automation of the station history log and site log management in order to improve and clarify the update process. This was realized by the site log manager which allows stations to update their log on-line on the EDC website. In this step, the site log format (version 2) was released which contains 18 updated and 100 new fields. The site logs from all stations have now been converted to version 2, which is now the standard format.

New Leap Second Procedure

The inconsistent handling of leap seconds in CPFs from different prediction providers and in different stations' software led to confusion and data loss around the time of the introduction of a leap second. Therefore, the DFPSC formulated a new procedure which proposed to stop tracking during leap seconds – the "coffee break approach".

Future Plans

The main objective of the DFPSC through the end of 2021 is to coordinate the implementation phase of the new CRD and CPF, which contains several milestones shown in Table 9-5.

Table 9-5. Implementation Plan for Version 2 of CRD/CPF Formats

January 2019	–	OCs, DCs should be able to handle v2 CPFs and CRDs
	–	At least one prediction provider should be producing v2 CPFs
	–	Some analysts should be able to process v2 CRD files
February 2019	–	OCs, DCs should be able to handle v2 CRDs
March 2019	–	Some analysts should be able to process v2 CRD files
December 2019	–	Almost all stations should be able to use v2 CPFs (required for those tracking ELT)
December 2020	–	All prediction providers should be producing v2 CPFs All analysts should be able to process v2 CRD files
December 2020	–	Almost all stations should be producing v2 CRDs
December 2021	–	Goal for discontinuing CPF v1 distribution

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Missions Standing Committee (MSC)

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Chair: Toshimichi Otsubo (Stephen Merkowitz starting mid-2019)
Co-Chair: Scott Wetzel (Toshimichi Otsubo starting mid-2019)

Summary

In the 2016-2019 period, the ILRS Missions Standing Committee (MSC) hosted three annual meetings in Potsdam, Riga and Canberra, all in conjunction with the ILRS-hosted workshops. A large majority of the standing committee discussions are conducted via email communications. In 2016, the name of this group is changed from Missions Working Group to Missions Standing Committee. In 2017, we largely updated the member list by removing six persons and adding three persons. In mid-2019, Stephen Merkowitz took over the role of MSC Chair with Toshimichi Otsubo remaining as the co-chair until 2020 when Robert Sherwood will take over co-chair responsibilities.

Two significant activities occurred during the 2016-2019 timeframe and are summarized in this report: the revision of Mission Support Request Form and the reconstruction of GNSS webpages. A list of newly approved missions is also included.

Revision of the ILRS Mission Support Request Form

The Mission Support Request Form (MSRF) was developed by the MSC, with concurrence of the ILRS Central Bureau (CB). Missions requesting SLR tracking support must complete this form in order to provide information required to enable the ILRS to determine if future laser ranging to the satellite is warranted. The form allows for the mission to provide important information, including key contacts, mission descriptions, and satellite and laser retroreflector array characteristics that will allow the ILRS to assess the use of the SLR data in the development of science data products and to provide the mission with the SLR data that supports their goals. The MSC also reviewed submitted MSRFs and provided recommendations and feedback to the CB and GB for future mission support.

In 2016, the Standing Committee revised the MSRF. Based on past experience with mission approval, the MSC re-designed the form to help mission sponsors more easily complete the form and to remove some ambiguous questions. An additional improvement to the form simplifies the approval process for follow-on missions, enabling an “incremental submission” in which only renewed information is required. The revised MSRF can be downloaded from the ILRS website (*https://ilrs.gsfc.nasa.gov/missions/mission_support*).

The MSC also updated the MSR submission scheme in 2018: the Mission Support Request Form must now be submitted at least six months prior to launch or from when mission expects tracking support to begin. The MSC clearly specified seven critical points which the ILRS must consider through the review stage. The new support guidelines are available on the ILRS website at URL: *https://ilrs.gsfc.nasa.gov/missions/mission_support/new_mission_support.html.*

Updates to GNSS Mission Webpages

Each mission supported by the ILRS has its own set of webpages within the ILRS website. These pages include detailed information about the satellite’s retroreflectors. For GNSS, however, there are a number of satellites with the same or similar configurations, and the ILRS website had not always contained updated information. Collaborating with the ILRS CB, in 2018, we reconstructed the mission webpages for GNSS satellites with the links to the Mission Support Request Forms, or the submitted supplementary information containing retroreflector details. We completed the updates for Galileo, BeiDou, and QZSS; updates for GLONASS and IRNSS have not yet been completed.

Recently Approved Missions

Missions approved during the reporting period include: Sentinel-3A/B, Lomonosov, COSMIC-2, QZS, BeiDou, TechnoSat, ICESat-2, S-NET, GRACE Follow-On, GEO-IK-2, LightSail-2, RANGE, CHEFSat, Tiangong-2, HY-2B, PAZ, Astrocast, and BLITS-M. It should be noted that small satellites are being planned with retroreflectors and some mission sponsors are new to the ILRS.

Future Plans

The observability of laser ranging is limited: a laser ranging station can observe only under a clear sky and track one satellite at a time. Having nearly one hundred targets in space (and increasing) and only a few tens of busy stations, we will not be able to approve every mission proposal as suggested in the newly adopted guideline. At the same time, a new topic “Mission Tracking Feedback” has been created within the Networks and Engineering Standing Committee Forum (special thanks to M. Wilkinson, NERC UK):

http://sgf.rgo.ac.uk/forumNESC/index.php?board=23.0

which is designed to exchange observing experiences not just among laser ranging stations but also with mission sponsors.

It is also important to strengthen the collaboration with other services, such as the IGS, the IDS, and the GGOS Standing Committee on Satellite Missions, since the “space tie” among different techniques nowadays has great value.

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Networks and Engineering Standing Committee (NESC)

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Chair: Matthew Wilkinson
Co-Chair: Georg Kirchner

Role of the Networks and Engineering Standing Committee

The Networks and Engineering Standing Committee (NESC) exists in the ILRS to draw on the experience, knowledge, and creativity in the global network in order to advance the satellite laser ranging technique and boost the performance of every station. It aims to strengthen the network links to promote collaboration, information sharing and best practice. The diversity that exists in the network is advantageous because by comparing and contrasting station performance and data quality, alongside the different hardware and software used, the best techniques and instrumentation can be identified. Any upgrade at one station could also potentially benefit others. The NESC can offer a network, technical perspective to other ILRS bodies (such as the Governing Board, Central Bureau, or other SCs) that is informed by the operational experience of its members.

Recent Achievements

The Beam Divergence Procedure was carried out by the majority of SLR stations in the ILRS network. It was shown to be an efficient and reliable method to determine the emitted laser beam divergence and the results largely agreed with the values recorded in the ILRS site logs, as shown in the bar chart below. The results are available on the ILRS website: *https://ilrs.gsfc.nasa.gov/docs/2018/BeamDiv_writeup.pdf*.

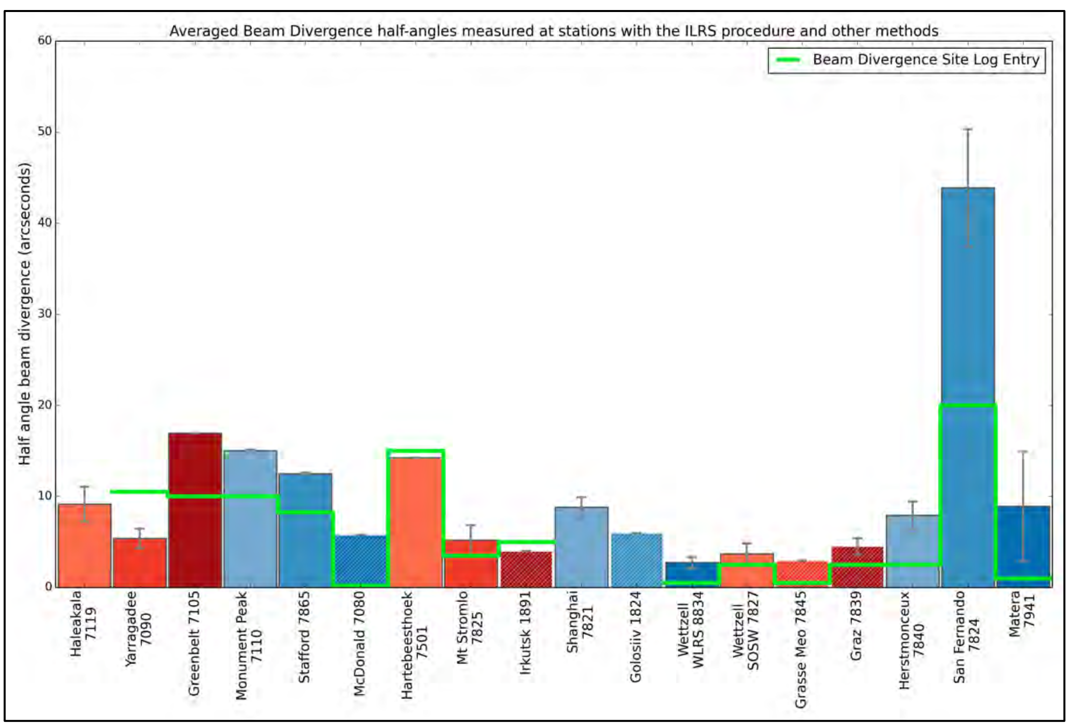

Figure 9-20. Results of the NESC's beam divergence procedure implemented at stations in the ILRS network.

An online forum for the NESC, and for the wider ILRS community, was launched (*http://sgf.rgo.ac.uk/forumNESC*) to encourage knowledge sharing, collaboration and community support. It currently has 84 members and is open for registration. A series of discussions now exist under the two main categories of 'General Topics' and 'Questions to the NESC Forum'. The topics for discussion are organized in 'boards', such as 'Station Performance' and 'Station Equipment Questions'. Members can start new topics and post replies to existing topics. All members of the NESC are encouraged to be active participants and to invite their colleagues to join this online community.

The NESC provided input to the new ILRS site log format over the course of its review. A recommendation was made by the NESC to encourage a standard approach to the full-rate data files that would ensure that all successful SLR returns are recorded. The NESC approved a list of criteria to be used in the quality control of CRD SLR data submitted to the ILRS Data Centers.

Current Activities

A reorganization of the NESC is underway. It is proposed that small panels are formed to address specific issues and to drive progress on important topics. The NESC meetings will be focused on reviewing the work of these panels and making decisions and recommendations accordingly. A schematic of how the NESC would work is shown below.

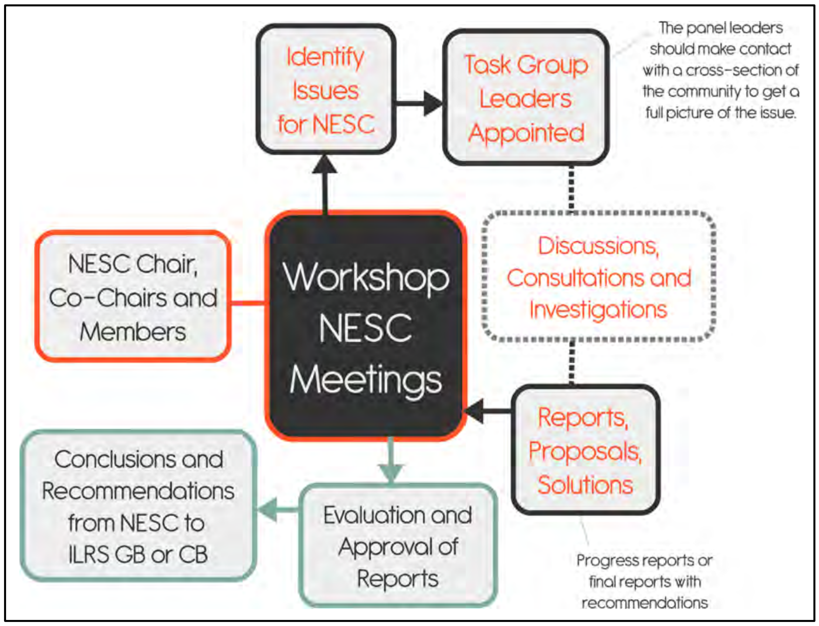

Figure 9-21. Plans for the reorganization of the NESC processes.

The NESC operations, including the annual meetings, could better serve the needs of the ILRS. The strength of the NESC is its membership, who can identify the important issues, hold discussions and arrange experiments, find solutions and make reports back to the NESC. The NESC meetings would then include:

- Determining priorities and problems
- Identifying individuals to work on the issues
- Reviewing reports to the NESC that detail how an issue was considered and resolved.
- Once an issue is resolved, recommendations can be drafted and sent to the appropriate ILRS body.

Future Plans

Once the restructuring of the operations of the NESC is complete, the NESC should aim to make progress and find resolutions to the most pressing issues. For illustration, these issues could include:

- Monitoring a station invariant point and the impact of temperature change
- Alternative methods to calculate a normal point
- Tracking scheduling for the GNSS and the increasing number or targets
- Station performance criteria to reflect all of the work done at stations
- Meteorological measurements at SLR stations
- Accuracy of the timing references at SLR stations

It would currently not be at all possible to address these questions, as valid as they may be, in the annual one-hour NESC meetings. The NESC online forum offers some space to advance discussion, but the NESC needs to operate in a way that it can help to address these concerns and others.

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Transponder Standing Committee (TSC)

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Chair: Ulrich Schreiber
Co-Chairs: John Degnan, Jan McGarry

Summary

Over the last several years there were three major activities on the agenda of the Transponder Standing Committee. These were the one-way ranging to the Lunar Reconnaissance Orbiter (LRO), the preparations of the upcoming time transfer mission “Atomic Clock Ensemble in Space” (ACES) and the time transfer by diffuse reflection on selected space debris items.

Recent Achievements and Current Activities

One-way ranging supported the LRO mission by improving the clock on the satellite. LRO also carried a cube corner reflector, which was eventually successfully tracked in a two-way ranging configuration by the MeO station in Grasse. Earlier ranging attempts from the Apache Point Observatory Lunar Laser ranging Operation (APOLLO) station failed. Retrospectively, it turned out that this was due to erroneous orbit predictions.

The ACES mission has faced many delays. These delays are mostly caused by technical issues in the two-way microwave link. The launch date has now been shifted to the second half of 2019. Current committee activities are still dealing with laser safety requirements. While the general safety concept is approved, a formal acceptance test of the implementation is still required. The Wettzell Laser Ranging System (WLRS) is acting as a model station in this respect, both for a high power and a low power operation setting. Once this system has been cleared for ISS tracking, other stations have a much-simplified acceptance procedure.

Laser time transfer is a key technology for a future relativistic geodesy, where highly resolved time, tied rigidly to geometric frame of reference is a key feature. Small and varying system delays are not detectable unless they can be referenced to time. Improving the time transfer capability therefore allows the quantification and an improvement of the long-term station stability.

Within the activities of the Transponder Standing Committee are also alternative ground to ground optical clock synchronization techniques. One promising approach is the asynchronous laser time transfer by diffuse reflection on suitable space debris items, where two laser station in common view are tracking a debris object like a burned-out upper stage of a launch vehicle. Each of the laser stations are obtaining their own ranges as well as the respective diffusely scattered laser pulses from the other station. Modeling the tumbling motion of the space debris item removes most of the experienced delay from the apparent target depth of the reflecting surface of the debris object. The first results from the observations of one station are encouraging.

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Space Debris Study Group (SDSG)

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Chair: Georg Kirchner
Co-Chair: Ludwig Grunwaldt

Summary

The mission of the Space Debris Study Group (SDSG) is to coordinate efforts of the SLR stations interested in the development, operation and utilization of the space debris laser ranging capabilities for the benefit of space science (Pearlman, et al., 2018).

Recent Achievements and Current Activities

The group has conducted a joint tracking campaign to the decommissioned TOPEX/Poseidon (T/P) satellite and collected a significant amount of full-rate laser range observations that are deposited on an open-access data server established and operated by the Space Research Institute of the Austrian Academy of Sciences (Graz, Austria) (*ftp://sddis.oeaw.ac.at*). The collected data have been used to investigate the Solar Radiation Pressure effects on the passive satellite treated as a sensor of the environmental forces and torques that perturb its orbital dynamics (Kucharski, Kirchner, Bennett, 2017). It has been found that the photon pressure torque exerted on the defunct T/P does not exceed 150 µNm and is responsible for the observed spin-up of the body from the stable nadir pointing position to a fast spinning state with a period of nearly 10 s. The laser ranges are also collected on other cooperative and non-cooperative space debris objects including rocket bodies and decommissioned GNSS satellites.

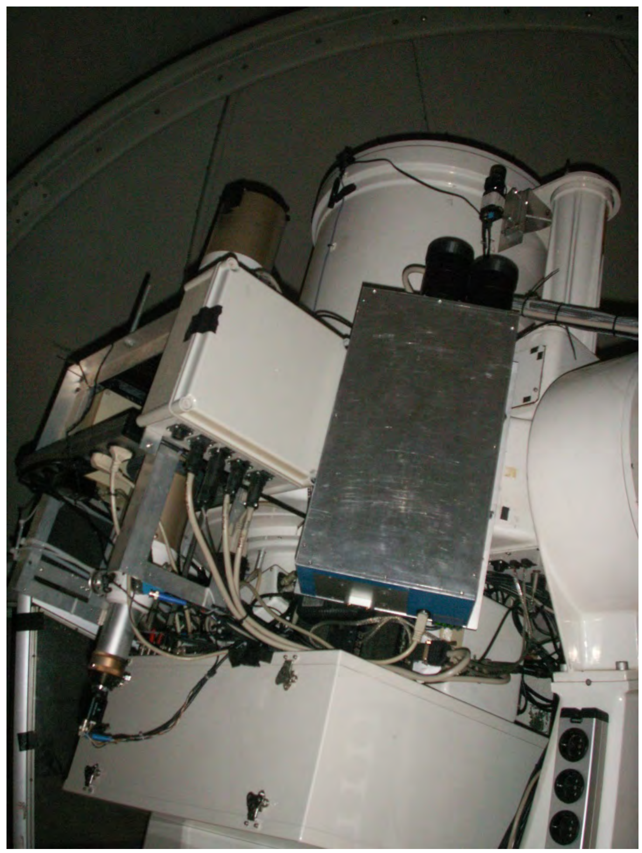

Figure 9-22. Space debris laser ranging system installed directly on Graz main laser telescope.

The Graz SLR station continues the development of the technology solution that brings the laser ranging capabilities to the astronomical telescopes (Figure 9-21). The compact laser system delivers 532 nm / 16 W / 200 Hz / 10 ns pulses; OR 1064 nm / 1064 nm / 32 W / 200 Hz / 10 ns); it is mounted directly on the telescope, avoiding the usual Coudé path. This setup improves the pointing stability and strengthens the link budget during the space debris laser ranging. The solution has been successfully tested in multiple tracking sessions and delivered hundreds of passes of various debris targets (Steindorfer et al., 2019). The achievable range accuracy is in the order of 0.5 m RMS and is limited by the ns laser pulses and large target sizes. The insufficient ephemeris accuracy restricts the debris laser ranging to the nighttime operation, but the work is in progress to extend the debris laser tracking to a full day activity by improving predictions and target visibility.

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Quality Control Board

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Chair: Michael Pearlman

Summary

System biases have plagued SLR since its inception. Both short and long-term biases can degrade the quality of the ILRS data products and alienate the ILRS user community. As an example: short-term biases reduce the available data and corrupt orbits on supported altimetry missions; long-term systematic effects can be aliased into geophysical data products, in particular reference frame products.

The Quality Control Board was organized at the 19th International Workshop on Laser Ranging, held in Annapolis, MD in October 2014, to address SLR systems biases and other data issues that have degraded the ILRS data and data products. The board is a joint activity under the Analysis Standing Committee (ASC) and the Networks and Engineering Standing Committee (NESC). The board meets periodically by telecon or in person. Activities and notes from board meetings are provided on the ILRS website: *https://ilrs.gsfc.nasa.gov/science/qcb/index.html*.

Recent Achievements and Current Activities

Current activities include:

- Study on what return pulse statistical information can reveal about ranging systematic errors (Peter Dunn)
- Comparison of Normal Points generated at the field stations with those generated by an open source Normal Point program (Randy Ricklefs, Matt Wilkinson)
- Examination of systematic data issues revealed by Analysis Center generated data products (Van Husson)

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Section 10:

ILRS Meeting Summaries

Section 10: ILRS Meeting Summaries

Authors: *Carey Noll, Michael Pearlman*
Responsible Agency: ILRS Central Bureau

Introduction

The ILRS sponsors International Workshops on Laser Ranging, typically held every two years. In recent years, the ILRS has conducted Technical or Specialized Workshops to focus on a few timely topics that impact the quality of ILRS data products and service operations. These workshops are held in intervening years between the full International Workshops on Laser Ranging and are intended to provide time to articulate the issues carefully, allow for in-depth discussion, and formulate a path forward.

This section provides summaries of those workshops held in the 2016-2019 time period and near-term plans for future workshops.

20th International Workshop on Laser Ranging

The Helmholtz Center Potsdam of the GFZ German Research Centre for Geosciences organized and hosted the 20th International Workshop on Laser Ranging Potsdam, Germany during the week of October 09–14, 2016. The meeting venue was located within the Science Campus "Albert Einstein" on top of the Telegrafenberg ("Telegraph Hill"), a place famous for both historic and modern science and one of the birthplaces of modern geodesy. Over 170 attendees (photo, Figure 10-1) from 25 countries participated in the meeting. The theme for this workshop, "The Path Toward the Next Generation Laser Ranging Network" allowed attendees to present ideas for future advances in SLR technology, science, and other applications.

Figure 10-1. Participants in the 20th International Workshop on Laser Ranging in Potsdam, Germany. (photo courtesy of L. Grunwaldt/GFZ).

Starting with overviews of recently achieved science and applications results through SLR, presentations reviewed current mission support and future requirements. With the increasing number of data users, the ILRS needs to a balance the user needs to the available network capacity, and look for ways to increase network utility. The meeting sessions then centered on SLR station related topics including station operations, data systematics and quality control, system co-locations on the ground and in space, network tracking strategies, experience with new hardware and software, etc. The meeting was planned to start sessions with focused talks and then give sufficient time for in-depth discussions, with conclusions and recommendations by the end of the Workshop. Time was made available starting on October 8 for dedicated ILRS Standing Committee, Study Group, Governing Board, and other splinter meetings. In addition, local staff hosted informal tours of the Potsdam SLR system during the week for interested attendees.

The workshop once again included a station operations or "clinic" session where ILRS experts met in small groups of station engineers and operators to discuss common station problems and issues, including stability of operational configurations, local means of diagnosing data problems, and guidelines for interacting with the analysts in determining station biases. These station clinics were well attended and received by workshop attendees.

The workshop program included over 80 oral presentations and over 60 posters. Each day began with an invited science talk highlighting SLR contributions. The workshop's proceedings website provides information about the workshop and its program and links to presentations, posters, session summaries, and contributed papers:

https://cddis.nasa.gov/lw20/

2017 ILRS Technical Workshop

The 2017 ILRS Technical Workshop, sponsored by the Institute of Astronomy at the University of Latvia and the ILRS, was held in Riga, Latvia, October 02-05. The theme for this meeting was "Improving ILRS Performance to Meet Future GGOS Requirements". Over 120 people (photo, Figure 10-2) from 21 countries participated in the meeting. The program included over 50 oral presentations, as well as many relevant posters.

The first day, session topics included discussions of user requirements and how well the ILRS is addressing these requirements. It started off with a reminder that laser ranging is one of the fundamental techniques for GGOS in its role of advancing our understanding of the dynamic Earth system by quantifying our planet's changes in space and time to advance Earth science and better understand processes to help us make intelligent societal decisions.

The second day of the workshop addressed how the ILRS evaluates current performance. Examination of network data on SLR satellites over many years has revealed interesting signatures correlated with the elevation and azimuth of the passes, day versus night-time conditions, and ascending vs. descending pass segments. The main focus is now on the sources of these systematic errors and how they map into our geodetic products. Some of these issues are errors in satellite center-of-mass models, data sampling, and incorrect modeling of system processing of return signals. The third day focused on obstacles that are currently limiting network output and operational steps that could improve ranging performance. Studies continue on using correlation techniques on the return signals to reduce range biases (particularly on the spherical passive satellite) and new potential methods for bias-free range measurements at the mm-level. The fourth day concentrated on automation and autonomous station operations. Representatives from many of the stations described their activities underway and plans from partial and fully automated scheduling and the application situational awareness from multi-sensor data. Challenges include area safety and aircraft avoidance, automating the signal discrimination, telescope pointing optimization, cloud and weather considerations, and dynamic (real-time) scheduling.

The workshop concluded with summary presentations from the chairs of the four sessions as well as the chairs of the standing committees and study groups. In addition, the participants supported resolutions that (1) urged to the community to seek more SLR stations in the southern Hemisphere, (2) asked the relevant agencies in Argentina and China to make every effort to complete the upgrade of the San Juan SLR station, and (3) thanked the University of Latvia and the local Organizing Committee for all of their work in making the Workshop a great success.

The workshop's proceedings website provides information about the meeting, the full program booklet, and links to abstracts, presentations, posters, session summaries, and contributed papers:

https://cddis.nasa.gov/2017_Technical_Workshop/

Figure 10-2. Participants in the 2017 ILRS Technical Workshop in Riga, Latvia. (photo courtesy of T. Grinbergs, University of Latvia).

21st International Workshop on Laser Ranging

The Space Environment Research Centre (SERC) and the ILRS hosted the 21st International Workshop on Laser Ranging at the John Curtin School of Medical Research, Australian National University in Canberra, Australia during the week of November 05-08, 2018. The theme of the workshop "Laser Ranging for Sustainable Millimeter Geoscience". Daily introductory presentations were given on topics highlighting SLR contributions to science (Geodynamics, ocean and ice altimetry, gravity field, etc.) The four-day workshop program was organized into nine oral sessions, and two poster sessions focused on the oral session topics. The last day of the week was devoted to a separate event, the International Workshop on

Space Debris Management; there is very close synergy between SLR and debris tracking and many of the network stations participate in both since the hardware and operational techniques are common. The Space Debris Study Committee within the ILRS organizes the activity.

The four-day workshop program was organized into nine oral sessions, and two poster sessions focused on the oral session topics. Topics of the first day included SLR contributions to GGOS and the challenge of the 1-mm accuracy for GGOS, inter-technique comparisons and synergies between SLR and other space geodetic techniques, and improvements in the SLR contribution to the terrestrial reference frame. Day two's sessions discussed applications of the SLR technique, such as validation and support for GNSS orbit determination, laser time transfer, spacecraft attitude determination, reflector panel resolution performance, new methods of gravity field estimation, and new applications through the use of constellations of nanosatellites. Presentations on the current status and future plans for the ILRS network provided an overview of current network performance and the deployment of new technology to improve that performance, automated processing with data discrimination procedures, and development of new modeling techniques for reducing range biases. Sessions on day three included presentations of new developments in retroreflector arrays, spacecraft engineering testing and the move toward expanded system automation, including software development in scheduling, visualization, data processing, and station performance assessment. The afternoon of day three was devoted to a station operations or "clinic" session where ILRS experts met in small groups of station engineers and operators to provide solutions to common station problems, techniques to monitor ranging system stability, and guidelines for interacting with the analysts in determining and discussing station biases. These station clinics were well received and attended by workshop participants. The sessions on the final day of the laser ranging workshop focused on new technologies to improve performance, and help standardize and simplify SLR/LLR systems, and the use of existing technologies for new SLR applications such as laser communication and space debris monitoring. The last topic reviewed recent progress in Lunar Laser Ranging and lunar reflector technology.

Figure 10-3. Participants in the 21st International Workshop on Laser Ranging, Canberra, Australia. (photo courtesy of Exclusive Images, Canberra, Australia).

Over 175 registrants (photo, Figure 10-3) from 23 countries participated in the laser ranging workshop; 20 additional attendees, mainly from Australia, participated in the one-day space debris workshop. The workshop program included 80 oral presentations and over 60 posters; 25 oral presentations and 15 posters were given at the Space Debris Workshop.

All abstracts, presentations, posters, and summary papers from both workshops are available within the Program section of the workshop's proceedings website:

https://cddis.nasa.gov/lw21/

Additional information, such as meeting summaries, photos, and the full program booklet are available through this website.

2019 ILRS Technical Workshop

The 2019 ILRS Technical Workshop was hosted by DLR in Stuttgart, Germany, October 21-25, 2019. The theme of the workshop was "Laser ranging: To improve economy, performance, and adoption for new applications" with presentations that focused on new concepts and ideas on the future of laser ranging, in particular, how the ILRS can make the technique more productive and more cost effective. The resulting program for the 2019 ILRS Technical Workshop included sessions on improving current station performance, new applications, safety and security, and novel concepts to improve the SLR network.

The introductory session consisted of several invited talks to illustrate the current state of the ILRS network and its possible evolution over the next few years. Subsequent sessions focused on improving systems, synergies with other techniques and technologies, and plans for future systems. The final session included presentations on laser safety in particular aircraft detection.

To encourage discussion and exchange among the participants, some sessions included dedicated time slots for panel discussions. Dedicated poster sessions were also included in the program with time for attendees to browse and interact with authors. The workshop also included a tour of the two SLR stations in Stuttgart.

Prior to the 2019 ILRS Technical Workshop, the ILRS scheduled a one-day introductory course to give non-practitioners in SLR an opportunity to broaden their knowledge about laser ranging to Earth-orbiting satellites and the Moon. The course also provided attendees with some experience in the field an opportunity to refresh and strengthen their knowledge and increase their appreciation of this powerful measurement technique that supports geoscience and applications. The program for this one-day "SLR School" is also included in the 2019 ILRS Technical Workshop website.

Talks were given in a tutorial format, with time for questions and discussion. Interested parties were able to attend the school with or without participating in the Workshop. Tutorials differed in length depending on the topic, but each session left ample time for questions and discussion.

The one-day SLR School was a great way for attendees to get an overview of an important component of the space geodesy measurement constellation. The school proved to be an opportunity for participants to obtain an overall view of satellite laser ranging and was the first time that such a school had been offered. The ILRS plans to hold these types of instructional sessions in the future.

With its 150 participants (see Figure 10-4) from more than twenty countries and more than seventy presentations (oral and poster), the workshop illustrated the importance of SLR and its application to international scientific research.

Figure 10-4. Participants in the 2019 ILRS Technical Workshop in Stuttgart, Germany. (photo courtesy of Paul Wagner/DLR).

All abstracts, presentations, posters, and supporting information from the workshop, including those from the SLR School, are available within the Program section of the workshop's proceedings website:

https://cddis.nasa.gov/2019_Technical_Workshop/

Other ILRS-Related Meetings

The ILRS standing committees and study groups hold regular meetings in conjunction with the International Workshops on Laser Ranging and ILRS Technical Workshops. The Analysis Standing Committee typically holds additional meetings prior to or after the yearly EGU General Assembly events. Announcements, summaries, presentations, actions, and other material from these meetings are linked under the activities section of each group's pages on the ILRS website. In many cases, this material can also be found within the workshop proceedings websites.

Future Plans

The next International Laser Ranging Workshop, the 22nd, is planned for the fall 2020 in Kunming China. The next ILRS Technical/Specialized Workshop will be held in Arequipa, Peru, hosted by the University of San Augustin in 2021. These timeframes for both of these future workshops may need to change, however, due to the global coronavirus pandemic of 2020.

Appendix:

ILRS Information

Appendix: ILRS Information

Contributing Organizations

Table A-1. Organizations Contributing to the ILRS

Agency	Country
Observatorio Astronómico Félix Aguilar (OAFA) of the Facultad de Ciencias Exactas, Físicas y Naturales (FCEFN) of the Universidad Nacional de San Juan (UNSJ)	Argentina
Geoscience Australia (GA)	Australia
EOS Space Systems Pty. Ltd.	Australia
Austrian Academy of Sciences	Austria
National Institute of Geophysics, Geodesy and Geography (NIGGG, formerly CLG/BAS)	Bulgaria
Observatorio Geodetico TIGO, Universidad de Concepción	Chile
Academia Sinica	China
Changchun observatory of National Astronomical Observatory	China
Chinese Academy of Surveying and Mapping (CASM)	China
Institute of Seismology, China Seismological Bureau	China
Innovation Academy for Precision Measurement Science and Technology, Chinese Academy of Sciences (CAS)	China
National Astronomical Observatories of China (NAOC), Chinese Academy of Sciences (CAS)	China
Shanghai Astronomical Observatory (SHAO), Chinese Academy of Sciences (CAS)	China
State Seismological Bureau	China
Yunnan Observatory, Chinese Academy of Sciences (CAS)	China
Technical University of Prague	Czech Republic
National Research Institute of Astronomy and Geophysics (NRIAG)	Egypt
Finnish Geodetic Institute	Finland
Groupe de Recherche en Geodesie Spatiale (GRGS)	France
Observatoire de la Côte d’Azur/Center d’Etudes et de Recherches Géodynamiques et Astrométrie (OCA/CERGA)	France
Observatoire de Paris	France
Tahiti Geodetic Observatory, University of French Polynesia (UFP)	French Polynesia
Bundesamt für Kartographie und Geodäsie (BKG)	Germany
Deutsches Geodätisches Forschungsinstitut-Technische Universität München (DGFI-TUM)	Germany
European Space Agency/European Space Operation Center (ESA/ESOC)	Germany

Table A-1. Organizations Contributing to the ILRS, continued

Agency	Country
German Aerospace Center (DLR) e.V.	Germany
Institut fuer Erdmessung/Forschungseinrichting SatellitenGeodasie (IFE/FESG)	Germany
Helmholtz Centre Potsdam GeoForschungsZentrum German Research Centre for Geosciences (GFZ)	Germany
Technische Universität München (TUM)	Germany
Agenzia Spaziale Italiana, Centro di Geodesia Spaziale "G. Colombo" (ASI/CGS)	Italy
Institute for Space Astrophysics and Planetology (IAPS)/National Institute for Astrophysics (INAF) and INFN-Roma2	Italy
Istituto Naz. di Fisica Nucleare - Laboratori Naz. di Frascati (INFN-LNF)	Italy
Hitotsubashi University	Japan
Hydrographic and Oceanographic Department, Japan Coast Guard	Japan
Japan Aerospace Exploration Agency (JAXA)	Japan
National Institute of Information and Communications Technology (NICT)	Japan
Tsukuba Space Center/JAXA	Japan
Institute of Astronomy, University of Latvia	Latvia
Delft University of Technology (DUT)	The Netherlands
Norwegian Mapping Authority (Kartverket)	Norway
Universidad Nacional de San Agustín de Arequipa (UNSA)	Peru
Space Research Center of the Polish Academy of Sciences (PAS)	Poland
Wroclaw University of Environmental and Life Sciences	Poland
Information-Analytical Center (IAC)	Russia
Institute of Applied Astronomy (IAA)	Russia
Institute of Astronomy of the Russian Academy of Sciences (INASAN)	Russia
Institute of Metrology for Time and Space (IMVP)	Russia
Pulkovo EOP and Reference Systems Analysis Center (PERSAC)	Russia
Research and Production Corporation "Precision Systems and Instruments"	Russia
Federal State Unitary Enterprise (FSUE), National Research Institute for Physical-Technical and Radio Engineering Measurements (VNIIFTRI)	Russia
Russian Mission Control Centre	Russia
Russian Space Agency (RSA)	Russia
Space Research Institute (SRI) for Precision Instrument Engineering	Russia
King Abdulaziz City for Science and Technology (KACST)	Saudi Arabia
Hartebeesthoek Radio Astronomy Observatory (HartRAO)	South Africa
South African Radio Astronomy Observatory (SARAO)	South Africa
Korea Astronomy and Space Science Institute (KASI)	South Korea
Real Instituto y Observatorio de la Armada	Spain
Instituto Geográfico Nacional, Observatorio de Yebes	Spain
Astronomical Institute, University of Berne (AIUB)	Switzerland

Table A-1. Organizations Contributing to the ILRS, continued

Agency	Country
Astronomical Observatory of the Ivan Franko National University of Lviv	Ukraine
Crimean Astrophysical Observatory RAS (CrAO RAS)	Ukraine
Lebedev Physical Institute in the Crimea	Ukraine
Main Astronomical Observatory (MAO) of the National Academy of Sciences (NAS) of Ukraine (GAOUA)	Ukraine
British Geological Survey	United Kingdom
NERC Space Geodesy Facility (NSGF)	United Kingdom
University of Newcastle Upon Tyne	United Kingdom
Center for Space Research (CSR), University of Texas at Austin	USA
Harvard-Smithsonian Center for Astrophysics	USA
Jet Propulsion Laboratory (JPL)	USA
Joint Center for Earth System Technology (JCET), University of Maryland, Baltimore County	USA
National Aeronautics and Space Administration Goddard Space Flight Center (NASA GSFC)	USA
Naval Research Laboratory (NRL)	USA
University of Hawaii Institute for Astronomy	USA
University of Texas at Austin	USA

Acronyms

AAC	Associate Analysis Center
AAG	Applied Astronomy Group (China)
AC	Analysis Center
ACES	Atomic Clock Ensemble in Space
ACT	Australian Capital Territory
ADEOS	Advanced Earth Observing Satellite
ADS-B	Automatic Dependent Surveillance-Broadcast
AG	Absolute Gravimeter
AGGO	Argentine-German Geodetic Observatory
AGU	American Geophysical Union (USA)
AIUB	Astronomical Institute of Berne (Switzerland)
ALOS	Advanced Land Observing Satellite
ALSEP	Apollo Lunar Surface Experiments Package
ANDE	Atmospheric Neutral Density Experiment (USA)
ANDE-RR	Atmospheric Neutral Density Experiment Risk Reduction (USA)
ANTL	Atmospheric Non-Tidal Loading
AO	Adaptive Optics
AOLC	Altay Optic-Laser Center (Russia)
APD	Avalanche Photodiodes
APOLLO	Apache Point Observatory Lunar Laser-ranging Operation (USA)
AR	Annual Report
ARB	Average Range Bias
ARSU	Amplified Receive Selection Unit
ASC	Analysis Standing Committee
ASI	Agenzia Spaziale Italiana (Italian Space Agency)
ASIMed	ASI Mediterranean (Italy)
AWG	Analysis Working Group
Az-El	Azimuth-Elevation
BE-C	Beacon Explorer C
BGS	British Geological Survey (UK)
BLITS	Ball Lens In The Space
BLITS-M	Ball Lens In The Space Modernized
BKG	Bundesamt für Kartographie und Geodäsie (Germany)
Cal/Val	Calibration/Validation
CAS	Chinese Academy of Sciences
CB	Central Bureau
CBK PAN	Centrum Badań Kosmicznych Polskiej Akademii Nauk (Poland)
CC	Combination Center

CCR	Corner Cube Reflector
CDDIS	Crustal Dynamics Data Information System (USA)
CEAS	Council of European Aerospace Societies
CfA	Center for Astrophysics (USA)
CGS	Centro di Geodesia Spaziale (Italy)
CHAMP	CHAllenging Mini-Satellite Payload
CHEFSat	Cost-effective High E-Frequency Satellite
CIRA	COSPAR International Reference Atmosphere
CLG	Central Laboratory for Geodesy (Bulgaria)
CMB	Core-Mantle Boundary
CMEMS	Copernicus Marine Environment Monitoring Service
CMONOC	Crustal Movement Observation Network of China
CMP	Conventional Mean Pole
CNES	Centre National d'Etudes Spatiales (France)
CNRS	National Centre for Scientific Research
CODE	Center for Orbit Determination in Europe
COG	Center of Gravity
CoM	Center of Mass
CONGO	Cooperative Network for GIOVE Observation
COOL	Combination On the Observation Level
CORS	Continually Operating Reference Station
COSMIC	Constellation Observing System For Meteorology, Ionosphere, and Climate
COSPAR	Committee on Space Research
COST-G	Combination Service for Time-variable Gravity Fields
COTS	Commercial Off The Shelf
COVID	Corona Virus Disease
CPF	Consolidated Prediction Format
CrAO	Crimean Astrophysical Observatory
CRD	Consolidated Laser Ranging Data format
CSN2	National Scientific Commission II (Italy)
C-SPAD	Compensated Single Photoelectron Avalanche Detector
CSR	Center for Space Research (USA)
CW	Continuous Wave
DEOS	Department of Earth Observation (The Netherlands)
DFPSC	Data Formats and Procedures Standing Committee
DGFI	Deutsches Geodätisches ForschungsInstitut (Germany)
DIRCO	Department International Relations and Cooperation (South Africa)
DLR	Deutsches Zentrum für Luft- und Raumfahrt (German Aerospace Center)
DLT	Debris Laser Tracking
DoD	Department of Defense (USA)
DOGS	DGFI Orbit and Geodetic Software (Germany)

DOR	Differential One-way Ranging
DORIS	Doppler Orbitography and Radiopositioning Integrated by Satellite
DS	Differential Scale
DTM	Drag Temperature Model
DUT	Delft University of Technology (The Netherlands)
EASEP	Early Apollo Scientific Experiment Package/Payload
EC	European Commission
ECOM	Empirical CODE Orbit Model
EDC	EUROLAS Data Center (Germany)
EGSIEM	European Gravity Service for Improved Emergency Management
EGU	European Geophysical Union
ELP	Ephémérides lunaires Parisienne (France)
ELPN	Ephéméride lunaire Parisienne Numérique (France)
ELS	European Lunar Symposium
ELT	European Laser Time Transfer Experiment
ENSO	El Niño-Southern Oscillation
EO	Earth Observation
EOP	Earth Orientation Parameter
EOS	Earth Observing System (USA)
EOS	Electro Optical Systems (USA)
EOSDIS	Earth Observing System Data Information System (USA)
EOST	EOS Technologies, Inc. (Australia)
EPM	Ephemeris of Planets and the Moon
ERP	Earth Rotation Parameter
ERS	European Remote Sensing Satellite
Er:YAG	Erbium Yttrium Aluminum Garnet
ESA	European Space Agency
ESAC	European Space Astronomy Center
ESOC	ESA Space Operations Center
ET	Event Timer
ETC	Event Timer Computer
ETM	Event Timer Module
ETS	Engineering Test Satellite
EU	European Union
EUREF	IAG Reference Frame Sub-Commission for Europe
EUROLAS	European Laser Consortium
FAA	Federal Aviation Administration (USA)
FESG	Forschungseinrichting Satellitengeodäsie (Research Facility for Space Geodesy, Germany)
FFI	Forsvarets ForskningsInstitutt (Norwegian Defense Research Establishment)
FGI	Finnish Geospatial Research Institute

FOC	Full Operational Capability
FPGA	Field Programmable Gate Array
FR	Full-Rate
FRD	Full-Rate Data
FSUE	Federal State Unitary Enterprise (Russia)
FTLRS	French Transportable Laser Ranging System
FTP	File Transfer Protocol
FWHM	Full width at half maximum
GA	Geoscience Australia
GAOUA	Main Astronomical Observatory of the National Academy of Sciences of Ukraine
GB	Gigabyte
GB	Governing Board
GCC	Geocenter Coordinates
GeoDAF	Geodetical Data Archive Facility (Italy)
GEO	Geosynchronous Earth Orbit
GEO	Group on Earth Observations
GEOS	Geodetic and Earth Orbiting Satellite
GFZ	GeoForschungsZentrum (Germany)
GGAO	Goddard Geophysical and Astronomical Observatory (USA)
GGOS	Global Geodetic Observing System
GIA	Glacial Isostatic Adjustment
GIOVE	Galileo in Orbit Validation Experiment
GIS	Geographic Information System
GLAS	Geoscience Laser Altimeter System (USA)
GLM	Geostationary Lightning Mapper
GLONASS	Global Navigation Satellite System
GLONASS	Global'naya Navigatsionnay Sputnikovaya Sistema
GM	Gravitational Constant
GMSL	Global Mean Sea Level
GNSS	Global Navigation Satellite System
GOCE	Gravity Field and Steady-state Ocean Circulation Explorer
GOES	Geostationary Operational Environmental Satellite
GOVUS	multi-GNSS Orbit Validation Visualizer Using SLR
GOW	Geodetic Observatory Wettzel (GOW)
GPS	Global Positioning System
GR	General Relativity
GRACE	Gravity Recovery And Climate Experiment
GRACE-FO	Gravity Recovery And Climate Experiment Follow-On
GRAIL	Gravity Recovery and Interior Laboratory
GREAT	Galileo gravitational Redshift test with Eccentric sATellites
GRGS	Groupe de Recherches de Geodesie Speciale (France)

GSI	Geospatial Information Authority of Japan
GSFC	Goddard Space Flight Center (USA)
GSTP	General Support Technology Programme
HartRAO	Hartebeesthoek Radio Astronomy Observatory (South Africa)
HEO	High Earth Orbiter
HFEOP	High Frequency EOP
Hit-U	Hitotsubatshi University (Japan)
HP	Hewlett-Packard
HQE	high quantum-efficiency
HxET	Herstmonceux Event Timer
Hz	Hertz
IAA	Institute of Applied Astronomy (Russia)
IAAPP	Instituto de Investigación Astronómico y Aeroespacial Pedro Paulet (Peru)
IAC	Information-Analytical Center (Russia)
IAG	International Association of Geodesy
IAPG/TUM	Institute of Astronomical and Physical Geodesy of the Technische Universität München (Germany)
IAPS	Institute for Space Astrophysics and Planetology (Italy)
IBGE	Instituto Brasileiro de Geografia e Estatística (Brazil)
ICG	International Committee on Global Navigation Satellite Systems
ICESat	Ice Cloud and Land Elevation Satellite
ICRF	International Celestial Reference Frame
ICRS	International Celestial Reference System
IDS	International DORIS Service
IEEE	Institute of Electrical and Electronics Engineers
IERS	International Earth Rotation and Reference Systems Service
IFE	Institut für Erdmessung (Germany)
IGFS	International Gravity Field Service
IGG	Institute of Geodesy and Geoinformatics (Poland)
IGLOS	International GLONASS Service
IGN	Institut Geographique National (France)
IGN	National Geographic Institute (Spain)
IGS	International GNSS Service
ILRS	International Laser Ranging Service
ILRSA	ILRS A solution
ILRSB	ILRS B solution
IMCCE	Institut de Mécanique Céleste et de Calcul des Éphémérides (France)
INAF	National Institute for Astrophysics (Italy)
INFN	Istituto Nazionale di Fisica Nucleare (Italy)
INPOP	Integration Numerique Planetaire de l'Observatoire de Paris (France)

INRRI	INstrument for landing-Roving laser Retroreflector Investigations (Italy)
IOV	In Orbit Validation
IR	Infrared
IRV	Inter-Range Vector
ISCEA	Institute of Seismology, China Earthquake Administration
ISI	Institute for Scientific Information
I-SOC	Space Optical Clock on ISS
ISRO	Indian Space Research Organization
ISS	International Space Station
ISTRAC	ISRO Telemetry Tracking and Command Network (India)
ITRF	International Terrestrial Reference Frame
ITRS	International Terrestrial Reference System
IUGG	International Union of Geodesy and Geophysics
IVS	International VLBI Service for Geodesy and Astrometry
IWLR	International Workshop on Laser Ranging
JAXA	Japan Aerospace Exploration Agency
JB	Jacchia-Bowman model
JCET	Joint Center for Earth Systems Technology (USA)
JGM	Joint Gravity Model
JGR	Journal of Geophysical Research
JPL	Jet Propulsion Laboratory (USA)
KASI	Korea Astronomy and Space Science Institute (South Korea)
kHz	Kilohertz
KOMPSAT	Korea Multi-Purpose Satellite
kVA	Kilo Volt Ampere
LAAC	Lunar Associate Analysis Center
LAGEOS	LAser GEOdynamics Satellite
LARA	Laser Retroreflector Array
LARASE	LAser RAnged Satellites Experiment
LAREG	Laboratoire de Recherches en Géodésie (France)
LARES	Laser Relativity Satellite
LARGE	LAser Ranging to GNSS s/c Experiment
LARRI	Laser RetroReflector for InSight
LASSOS	LArase Satellites Spin mOdel Solutions
LEO	Low Earth Orbit
LGN	Lunar Geophysical Network
LHRS	Laser Hazard Reduction System
LIDAR	Light Detection and Radar
LLR	Lunar Laser Ranging
LMA	Large Mode Area

LNF	Laboratori Nazionali di Frascati (Italy)
LOD	Length Of Day
LOLA	Lunar Orbiter Laser Altimeter
LR	Laser Ranging
LRA	Laser Retroreflector Array
LRC	Laser Radar Control
LRO	Lunar Reconnaissance Orbiter
LRO-LR	Lunar Reconnaissance Orbiter Laser Ranging
LTT	Laser Time Transfer
MAO	Main Astronomical Observatory (Ukraine)
MCC	Mission Control Center (Russia)
MCP	Micro Channel Plate
MeO	Meteorology and Optics (France)
MEO	Medium Earth Orbit
MGEX	Multi-GNSS Experiment
MGN	Mars Geophysical Network
MGO	McDonald Geodetic Observatory (USA)
MHB	Mathews-Herring-Buffett model
MHz	Megahertz
MJ	Millijoules
MLRO	Matera Laser Ranging Observatory (Italy)
MLRS	McDonald Laser Ranging System (USA)
µm	Micrometer
MOBLAS	MOBile LASer Ranging System
MOMS	Mobile Optical Mount System
MoonLIGHT	Moon Laser Instrumentation for General relativity High- Accuracy Tests
MP	Mean Pole
MPACS	Mount Positioning and Control Subsystem
MPD	Micro Photon Device
mrad	Milliradian
MSC	Missions Standing Committee
MS-LART	Multi-Spectral Large Aperture Receiver Telescope
MSR	Mission Support Request
MSRF	Mission Support Request Form
Mt. FUJI	MulTiple reFlector Unit from JAXA Investigation (Japan)
MWG	Missions Working Group
NAO	National Astronomical Observatories (China)
NAOC	National Astronomical Observatories of China
NAPEOS	NAvigation Package for Earth Observation Satellites
NAS	National Academy of Sciences (Ukraine)

NASA	National Aeronautics and Space Administration (USA)
Nd:YAG	Neodymium Yttrium Aluminum Garnet
NEOS	National Earth Orientation Service (USA)
NEQ	Normal Equation
NERC	Natural Environment Research Council (UK)
NESC	Networks and Engineering Standing Committee
NICT	National Institute of Information and Communications Technology (Japan)
NISAR	NASA-ISRO SAR
NOAA	National Oceanic and Atmospheric Administration (USA)
NP	Normal Point
NPET	New Pico Event Timer
NPT	Normal Point
NRL	Naval Research Laboratory (USA)
NRLMSISE	NRL Mass Spectrometer and Incoherent Scatter Radar
nm	Nanometer
ns	Nanosecond
NSGF	NERC Space Geodesy Facility (UK)
NSW	New South Wales (Australia)
OC	Operations Center
OCA	Observatoire de la Côte d'Azur (France)
OGT	Observatoire Géodésique de Tahiti (French Polynesia)
OICETS	Optical Inter-orbit Communications Engineering Test Satellite (Japan)
OOOS	Orbital Objects Observation Software
OP-SYRTE	Observatoire de Paris Systèmes de Référence Temps-Espace (France)
OS	Operating System
OST	Operations Support Technician
OSTST	Ocean Surface Topography Science Team
OTA	Optical Tube Assembly
PAS	Polish Academy of Sciences
PCO	Phase Center Offset
PDF	Portable Document Format
PEP	Planetary Ephemeris Program
PERSAC	Pulkovo EOP and Reference Systems Analysis Center (Russia)
PLATO	Performance Simulations and Architectural Trade-Offs
PMF	Potsdam Mapping Function
PMT	Photo Multiplier Tube
POD	Precision Orbit Determination
POE	Precise Orbit Ephemerides
POLAC	Paris Observatory Lunar Analysis Center (France)
PP	Pilot Project

PPB	Part Per Billion
PPET	Portable Pico-Second Event Timer
PPN	Parametrized Post Newtonian
PPS	Part Per Second
ps	Picosecond
PSD	Post-Seismic Deformation
PSMSL	Permanent Service for Mean Sea Level
PSL	Paris Sciences et Lettres, Paris Observatory (France)
QC	Quality Control
Q/C	Quality Control
QCB	Quality Control Board
QKD	Quantum Key Distribution
QLNP	Quick-Look Normal Point
QUEST	Quantum Engineering and Space-Time Research (Germany)
QZS	Quasi-Zenith Satellite (Japan)
QZSS	Quasi-Zenith Satellite System (Japan)
R&D	Research and Development
RANGE	Ranging And Nanosatellite Guidance Experiment (USA)
RAS	Russian Academy of Sciences
RCC	Range Control Card
REGINA	Réseau GNSS pour l'IGS et la Navigation (France)
RG	Range Gate
RINEX	Receiver Independent Exchange format
RMS	Root Mean Square
ROA	Real Instituto y Observatorio de la Armada (Spain)
RPC PSI	Research and Production Corporation "Precision Systems and Instruments" (Russia)
RRA	Retro Reflector Array
RS/PC	Rapid Service/Prediction Center
RT	Radio Telescope
RTS	Riga Event Timing System
SARAL	Satellite with ARgos and ALtiKa
SAO	Shanghai Astronomical Observatory (China)
SAO	Smithsonian Astrophysical Observatory (USA)
SAR	Synthetic Aperture Radar
SARAO	South African Radio Astronomy Observatory
SATRAP	SATellite Reentry Analysis Program
SBAAM	IERS Sub Bureau for Atmospheric Angular Momentum
SC	Standing Committee
SCF	Satellite/lunar laser ranging Characterization Facility (Italy)
SCF	System Configuration File

SCW	Swenson, Chambers and Wahr Model
SDSG	Space Debris Study Group
SERC	Space Environment Research Centre (Australia)
SG	Superconducting Gravimeter
SGF	Space Geodesy Facility (UK)
SGP	Space Geodesy Project (USA)
SGSLR	Space Geodesy Satellite Laser Ranging System (USA)
SHAO	Shanghai Astronomical Observatory (China)
SHO	Shimosato Hydrographic Observatory (Japan)
SINEX	Software Independent Exchange Format
SIRGAS	Sistema de Referencia Geocéntrico para las Américas (Geocentric Reference System for the Americas)
SLR	Satellite Laser Ranging
SME	Standard Model Extension
SNET	S-Band Network for Cooperative Nanosatellites
SNR	Signal-to-Noise Ratio
SNSPD	Superconducting Nano-wire Single Photon Detector
SOD	Site Occupation Designator
SOLT	Space Optical and Laser racking (South Korea)
SOS-W	Satellite Observing System-Wettzell (Germany)
SP3	Standard Product 3 (satellite orbit format)
SPAD	Single Photoelectron Avalanche Detector
SPIE	International Society for Optical Engineering
SRC PAS	Space Research Centre of the Polish Academy of Sciences (Poland)
SSA	Space Situational Awareness
SSC	Set of Station Coordinates
SSEM	Systematic Station Error Monitoring
SSTF	State Service of Time, Frequency
SSV	Set of Station Velocities
SST	Satellite-to-Satellite Tracking
STAR-C	Surveillance, Tracking And Ranging – Container (Germany)
STR	Stuttgart Airport (Germany)
STSAT	Science and Technology SATellite (South Korea)
SYRTE	Systèmes de Référence Temps-Espace (France)
T2L2	Time Transfer by Laser Link
TanDEM	TerraSAR-X add-on for Digital Elevation Measurement
TD	Total Density model
TDB	Barycentric Dynamical Time
TDEV	Time Deviation
TDM	Tracking Data Message
TIGO	Transportable Integrated Geodetic Observatory

TIRV	Tuned Inter-Range Vector
Ti:Sap	Titanium Sapphire
Ti:Sapphire	Titanium Sapphire
TIU	Time Interval Unit
TLE	Two Line Element
TLRS	Transportable Laser Ranging System
TOF	Time-Of-Flight
TOPEX	Ocean TOPography Experiment
ToR	Terms of Reference
T/P	TOPEX/Poseidon
TPF	Topocentric Prediction Format
T/R	Transmit/Receive
TRF	Terrestrial Reference Frame
TROS	TRansportable Observation Station
TROS	Transportable Range Observation System
TSC	Transponder Standing Committee
TT	Terrestrial Time
TU	Technical University
TUM	Technische Universität München (Germany)
TUS	Tracking Ultraviolet Set-up
UAW	Unified Analysis Workshop
UK	United Kingdom
UMBC	University of Maryland Baltimore County (USA)
UnB	University of Brasilia
UNSA	Universidad Nacional de San Augustin (Peru)
UPF	Université de la Polynésie Française
UPS	Uninterruptible Power Supply
URL	Uniform Resource Locator
UROL	Uhlandshöhe Research Observatory (Germany)
USA	United States of America
USNO	U.S. Naval Observatory
USSR	Union of Soviet Socialist Republics
UT	University of Texas
UTC	Universal Coordinated Time
UV	Ultraviolet
VCE	Variance Component Estimation
VGOS	VLBI Global Observing System
VLBI	Very Long Baseline Interferometry
VNA	Vector Network Analyzer
VNIIFTRI	Russian Metrological Institute of Technical Physics and Radio Engineering

WESTPAC	Western Pacific Laser Tracking Network Satellite
WG	Working Group
WLRS	Wettzell Laser Ranging System (Germany)
WPLTN	Western Pacific Laser Tracking Network
WRMS	Weighted Root Mean Square
WUELS	Wroclaw University of Environmental and Life Sciences (Poland)
XAO	Xinjiang Astronomical Observatory (China)
YAG	Yttrium Aluminum Garnet
YLARA	Yebes LAser RAnging (Spain)
Yt:YAG	Ytterbium Yttrium Aluminum Garnet
ZARM	Center of Applied Space Technology and Microgravity (Germany)
ZD	Zenith Delay
ZIMLAT	Zimmerwald Laser and Astronomy Telescope (Switzerland)


NASA
IAG
International Laser Ranging Service