

International Laser Ranging Service (ILRS)

<https://ilrs.gsfc.nasa.gov>

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Overview

The ILRS is the international source that provides Satellite Laser Ranging (SLR) and Lunar Laser Ranging (LLR) observation data and data products for scientific and engineering programs with the main focus on Earth and Lunar applications. The basic observables are the precise two-way time-of-flight of ultra-short laser pulses from ground stations to retroreflector arrays on satellites and the Moon and the one-way time-of-flight measurements to space-borne receivers (transponders). These data sets are made available to the community through the CDDIS and the EDC archives, and are also used by the ILRS to generate fundamental data products, including: accurate satellite ephemerides, Earth orientation parameters, three-dimensional coordinates and velocities of the ILRS tracking stations, time-varying geocenter coordinates, static and time-varying coefficients of the Earth's gravity field, fundamental physical constants, lunar ephemerides and librations, and lunar orientation parameters.

SLR is one of the four space geodetic techniques (along with VLBI, GNSS, and DORIS) whose observations are the basis for the development of the International Terrestrial Reference Frame (ITRF), which is maintained by the IERS. SLR defines the origin of the reference frame, the Earth center-of-mass and, along with VLBI, its scale. The ILRS generates daily a standard product of station positions and Earth orientation based on the analysis of the data collected over the previous seven days, for submission to the IERS, and produces LAGEOS/Etalon combination solutions for maintenance and improvement of the International Terrestrial Reference Frame. The latest requirement is to improve the reference frame to an accuracy of 1 mm accuracy and 0.1 mm/year stability, a factor of 10–20 improvement over the current product. To address this requirement, the SLR community is working to improve the quantity and quality of ranging to the geodetic constellation (LAGEOS-1 and -2, Etalon-1 and -2, and LARES) to support the definition of the reference frame, and to the GNSS constellations to support the global distribution of the reference frame.

The ILRS participates in the Global Geodetic Observing System (GGOS) organized under the IAG to integrate and help coordinate the Service activities and plans.

ILRS Structure

The ILRS Organization (see Figure 1) includes the following permanent components:

- Network of tracking stations
- Operations Centers
- Global Data Centers
- Analysis and Associate Analysis Centers
- Central Bureau
- Governing Board
- Standing Committees (SCs)
 - Analysis
 - Data Formats and Procedures
 - Missions
 - Networks and Engineering
 - Transponders
- Study Groups (SGs) and Boards
 - Laser Ranging to GNSS s/c Experiment (LARGE)
 - Quality Control Board
 - Software Study Group
 - Space Debris Study Group

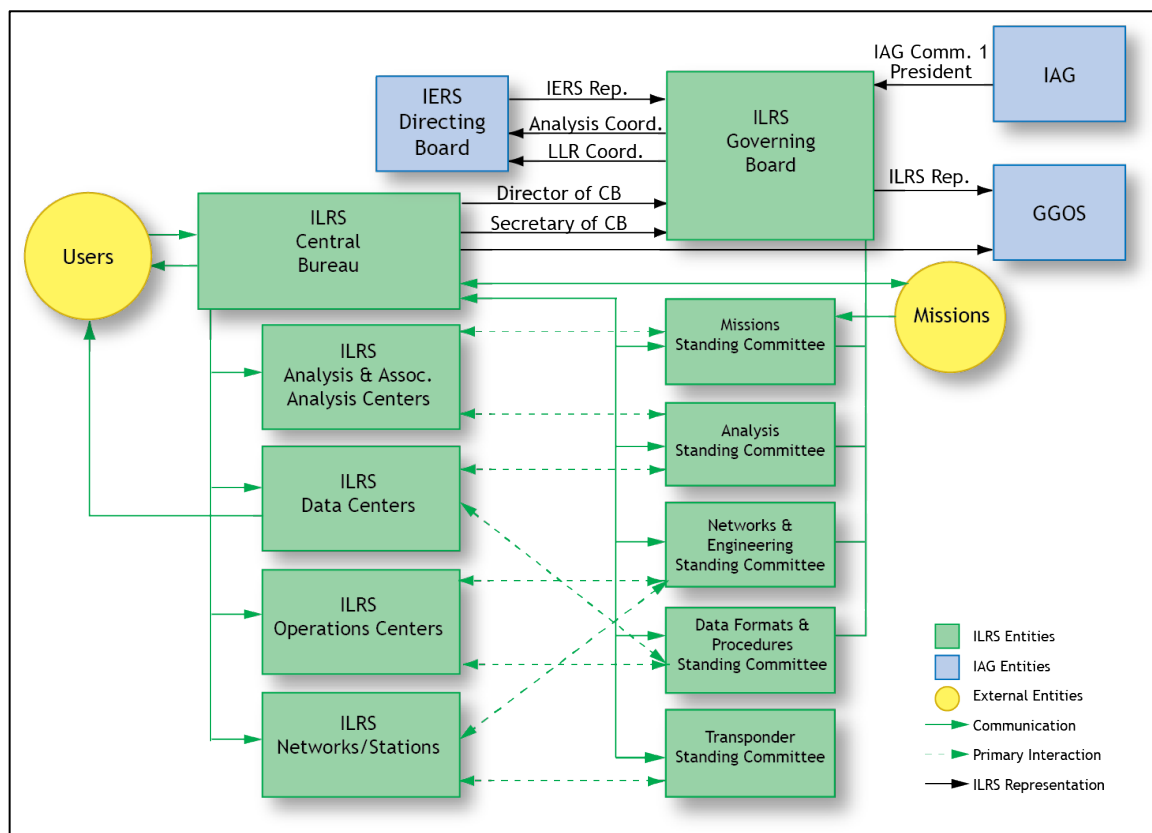


Figure 1. The organization of the International Laser Ranging Service (ILRS).

The role of these components and their inter-relationship is presented on the ILRS website (<https://ilrs.gsfc.nasa.gov/about/organization/index.html>).

The Governing Board (GB) is responsible for the general direction of the service. It defines official ILRS policy and products, determines satellite-tracking priorities, develops standards and procedures, and interacts with other services and organizations. The members of the current Governing Board, selected and elected for a two-year term, are listed in Table 1.

Table 1. ILRS Governing Board (as of May 2019)

Name	Position	Country
James Bennett	Appointed, WPLTN Network	Australia
Giuseppe Bianco	Appointed, EUROLAS Network, Governing Board Chair (2015-2018)	Italy
Urs Hugentobler	Ex-Officio, Representative of IAG Commission 1	Germany
Georg Kirchner	Appointed, EUROLAS Network, Networks and Engineering Standing Committee Co-Chair	Austria
Vincenza Luceri	Elected, Analysis Representative, Analysis Standing Committee Deputy Chair	Italy
Jan McGarry	Appointed, NASA Network	USA
Stephen Merkwowitz	Appointed, NASA Network	USA
Carey Noll	Ex-Officio, Secretary, ILRS Central Bureau	USA
Toshimichi Otsubo	Elected, At-Large, Governing Board Chair (2019-2020)	Japan
Erricos Pavlis	Elected, Analysis Representative, Analysis Standing Committee Chair	USA
Michael Pearlman	Ex-Officio, Director, ILRS Central Bureau	USA
Ulrich Schreiber	Appointed, At-Large, Transponder Standing Committee Chair	Germany
Christian Schwatke	Elected, Data Centers Representative, Data Formats and Procedures Standing Committee Chair	Germany
Krzysztof Sośnica	Appointed, At-Large	Poland
Daniela Thaller	Appointed, IERS Representative to ILRS	Germany
Jean-Marie Torre	Elected, Lunar Representative	France
Matt Wilkinson	Elected, At-Large, Networks and Engineering Standing Committee Chair	UK
Zhang Zhongping	Appointed, WPLTN Network	China
Former Governing Board Members during 2015-2019		
Wu Bin	Appointed, WPLTN	China
Geoff Blewitt	Ex-Officio, Representative of IAG Commission 1	USA
Ludwig Combrinck	Elected, Lunar Representative	South Africa
David McCormick	Appointed, NASA Network	USA
Horst Müller	Elected, Data Centers Representative, Data Formats and Procedures Standing Committee Chair	Germany
Jürgen Müller	Elected, Lunar Representative	Germany
Andrey Sokolov	Appointed, At-Large	Russia

The Central Bureau (CB) is responsible for the daily coordination and management of the ILRS in a manner consistent with the directives and policies established by the Governing Board. The primary functions of the CB are to facilitate communications and information transfer within the ILRS and between the ILRS and the external scientific community, coordinate ILRS activities, maintain a list of satellites approved for tracking support and their priorities, promote compliance to ILRS network standards, monitor network operations and quality assurance of data, maintain ILRS documentation and databases, produce reports as required, and organize meetings and workshops. The CB operates the communication center for the ILRS. The CB performs a long-term coordination and communication role to ensure that ILRS participants contribute to the Service in a consistent and continuous manner and that they adhere to ILRS standards.

Permanent Standing Committees (SCs) and temporary Study Groups (SGs) provide the expertise necessary to make technical decisions, to plan programmatic courses of action, and are responsible for reviewing and approving the content of technical and scientific databases maintained by the Central Bureau. All GB members serve on at least one of the five SCs, led by a Chair and Co-Chair (see Table 1). The SCs continue to attract talented people from the general ILRS membership who contributed greatly to the success of these efforts.

Data Products

The main ILRS analysis products consist of SINEX files of weekly-averaged station coordinates and daily Earth Orientation Parameters (x-pole, y-pole and excess length-of-day—LOD) estimated from 7-day arcs of SLR tracking of the two LAGEOS and two Etalon satellites. As of May 1, 2012, the official ILRS Analysis product is delivered on a DAILY basis by sliding the 7-day period covered by the arc by one day forward every day. This allows the ILRS to respond to two main users of its products: the ITRS Combination Centers and the IERS EOP Prediction Service at USNO. The former requires a single analysis per week; the latter however requires as “fresh” EOP estimates as possible, that the “sliding” daily analysis readily provides. Two types of products are distributed for each 7-day period: a loosely constrained estimation of coordinates and EOP and an EOP solution, derived from the previous one and constrained to an ITRF, which beginning on June 1, 2017, is ITRF2014. Official ILRS Analysis Centers (ACs) and Combination Centers (CCs) generate these products with individual and combined solutions respectively. Both the individual and combined solutions follow strict standards agreed upon within the ILRS Analysis Standing Committee (ASC) to provide high quality products consistent with the IERS Conventions. This description refers to the status as of May 2017. Each official ILRS solution is obtained through the combination of solutions submitted by the official ILRS Analysis Centers:

- ASI, Agenzia Spaziale Italiana
- BKG, Bundesamt für Kartographie und Geodäsie
- DGFI, Deutsches Geodätisches Forschungsinstitut
- ESA, European Space Agency
- GFZ, GeoForschungsZentrum Potsdam
- GRGS, Observatoire de Côte d’Azur (participation suspended for two years)
- JCET, Joint Center for Earth Systems Technology and Goddard Space Flight Center
- NSGF, NERC Space Geodesy Facility

Since 2016, the ILRS has released an additional operational product on a weekly basis following a pilot project period. These official products are precision orbits in standard SP3c formatted files for the four satellite targets (LAGEOS-1, -2, and Etalon-1, -2).

Following the adoption of ITRF2014, the ASC issued an extended version of the reference frame, the SLRF2014, which includes some two-dozen additional SLR sites that were not part of ITRF2014 model. A number of these are historical sites from the early years of SLR, prior to ILRS, and the rest are new stations that were established either during the development of ITRF2014 or after its release; in either case these sites did not have enough data to support their inclusion in the new ITRF. The ILRS products are available, via ftp from the official ILRS Data Centers CDDIS/NASA Goddard Space Flight Center and EDC/TUM/DGFI:

<ftp://cddis.nasa.gov/slr/products/pos+eop> and
<ftp://edc.dgfi.tum.de/pub/slr/products/pos+eop>).

The individual ILRS AC and CC product contributions as well as the combinations are monitored on a daily basis in graphical and statistical presentation of these time series through a dedicated portal hosted by the JCET AC at:

http://geodesy.jcet.umbc.edu/ILRS_AWG_MONITORING/

The main focus of the Analysis SC activities over the past two years was the improvement of modeling used in the reduction of the SLR data and generation of the official products for the development of ITRF2014, (Luceri et al., 2014). In particular, all ACs made major efforts to comply with the adopted analysis standards and the IERS Conventions 2010, the consistent modeling of low degree time-varying gravitation and the realistic modeling of the mean pole in computing the pole tide effects (Pavlis et al., 2014). Since the delivery of the preliminary and final versions of ITRF2014, the ASC has focused on evaluating them and providing feedback to ITRS for adjustments that led to the finally adopted version. The efforts to identify, quantify and contain systematic errors in the SLR data have continued with many new initiatives that ILRS feels necessary in order to improve data quality.

It is recognized that practices that will limit or mitigate the effect of systematic errors in the ILRS data, improve the final products through realistic description of geophysical processes, and strengthen the quality of the products include but are not limited to using LARES as an additional accurate target in developing the official products (Pavlis et al., 2015). In addition to that though, a new study group, the ILRS “Quality Control Board”, with members from all areas of expertise within the service, has been established to generate tools and procedures that will help the station engineers identify with confidence and as quickly as possible, issues with their data, before they get too far down the production line. More details on the initial results from this new initiative are given under the section for the ILRS ASC.

The LLR group is in the process of developing a unique data set of all available LLR data in the officially adopted CRD format, in order to better serve the community and to conform with the ILRS standards. In that vein the LLR group proposed an Associate Analysis Center for LLR, which has been readily accepted by the ILRS.

Satellite Laser Ranging

ILRS Network

The present ILRS network includes over forty stations in 24 countries (see Figure 2); some of these stations are undergoing refurbishment and upgrade. During the last five years, new stations joined the ILRS network in Badary, Baikonur, Irkutsk, Svetloe, Zelenchukskaya, (Russia), Sejong and Geochang (Korea), and Brasilia (Brazil) filling-in very important geographic gaps. The Russian groups have advanced the idea of placing two SLR stations at critical locations to help address the tracking load. They have co-located a second station at Mendeleev and an SLR station with the NASA MOBLAS-6 at Hartebeesthoek (South Africa). The Russians are also planning installations of new SLR systems in Ensenada (Mexico), Java (Indonesia), and Grand Canary Island in the 2020 – 21 time frame, and have offered to co-locate new systems at stations currently operated by other organizations. The core Argentine-German Geodetic Observatory (AGGO), formally TIGO in Concepción, Chile, has been relocated to La Plata (Argentina); the SLR system is being upgraded and operations are expected to resume in late 2019. Work continues on the new station in Metsahövi (Finland) and the upgrade of the Chinese SLR station in San Juan (Argentina) both planned for operations in late 2019 or early 2020. Two new stations, are underway at Ponmudi and Mt. Abu (India) and planning is underway on a new in SLR station in Yebes (Spain). The NASA Space Geodesy Project (SGP) is building new SGSLR stations (as part of Core sites) at McDonald, TX, Haleakala, HI and NASA/GSFC. A fourth SGSLR system is being built in cooperation with the

Norwegian Mapping Agency (NMA) for Ny Ålesund (Norway). Operations are projected for the 2021–2022 timeframe. Planning is underway for additional SLR systems as part of core sites at other current NASA partner sites and new locations to help fill some of the geographic gaps in the global space geodesy network.

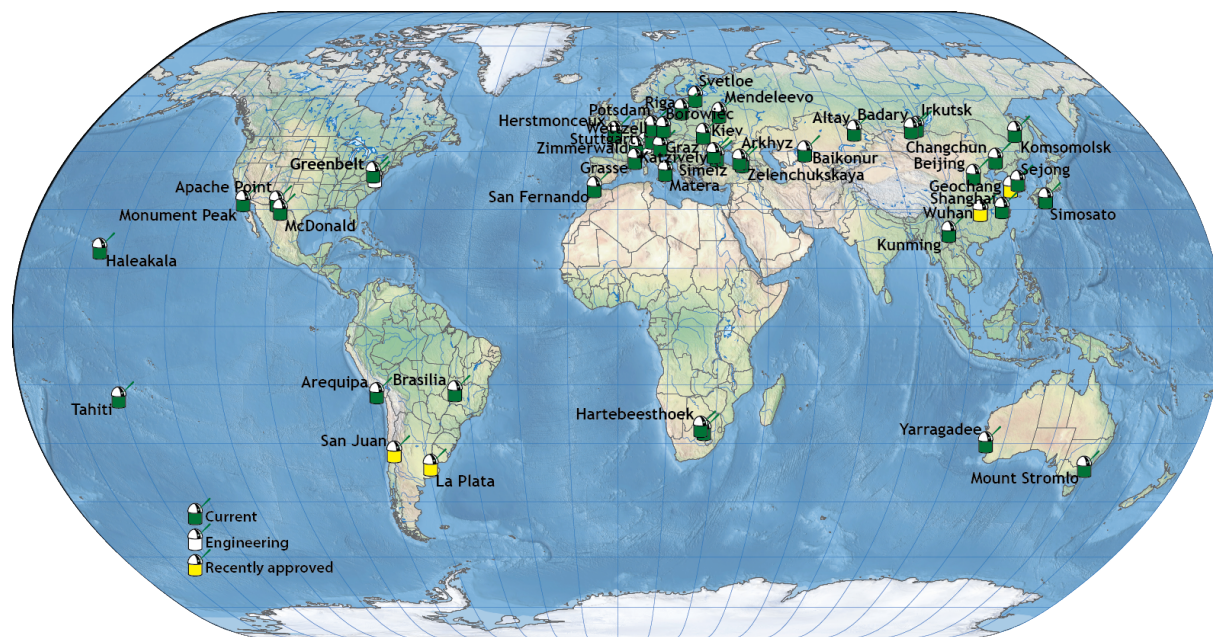


Figure 2. ILRS network (as of May 2019).

Large gaps are still very prominent in Africa and South America and discussions are underway with several groups in the hope of addressing this shortcoming.

Stations designated as operational have met the minimum ILRS qualification for data quantity and quality. In 2015, the ILRS Governing Board approved a new ILRS Pass Performance Standard of 3500 passes per year as an interim step toward a more comprehensive long-term strategy:

- 2 passes per week on each LEO satellite (2300 LEO passes per year)
- 4 passes per week on LAGEOS and LARES satellites (600 MEO passes per year)
- 2 passes per week on each HEO satellite (>3000 HEO passes per year)

In general stations continue to improve their performance; recent strong performers are shown in Figure 3. During the twelve-month period from May 2018 to April 2019, seventeen stations met the updated ILRS minimum requirement for total numbers of passes tracked (see Figure 3).

As shown in Table 2, several stations are now operating with kHz lasers and fast detectors, thereby increasing data yield and allowing them to be more productive with pass interleaving, a critical step as the number of satellites being tracked with SLR is increasing dramatically. Many others, particularly the Russian stations, are operating in the 100 to 300 Hz range. Some stations have demonstrated mm precision normal points, a fundamental step toward addressing the new reference frame requirements.

Satellite Missions

The ILRS is currently tracking nearly 100 artificial satellites including passive geodetic (geodynamic) satellites, Earth remote sensing satellites (e.g., altimetry, gravity field), navigation satellites (GNSS), and engineering missions (see Figure 4). The large list of satellites is saturating some stations that are not fully manned and strategies are being examined to try to maximize station data value. Some stations have implemented automated procedures to expand operating hours. The stations with lunar capability are also tracking the lunar reflectors. In

response to this large roster of satellites, as well as for support of tandem missions (e.g., GRACE-A/-B, TanDEM-X/TerraSAR-X) and general overlapping schedules, most stations in the ILRS network are tracking satellites with interleaving procedures.

Table 2. High-Repetition Rate ILRS Stations (as of May 2019)

Site Name	Station	Repetition
Altay	1879	300
Arkhyz	1886	300
Badary	1890	300
Baikonur	1887	300
Beijing	7249	1000
Brasilia	7407	300
Changchun	7237	1000
Graz	7839	2000
Hartebeesthoek	7503	300
Herstmonceux	7840	2000
Irkutsk	1891	300
Komsomolsk	1868	300
Kunming	7820	1000
La Plata	7405	100
Mendeleevo	1874	300
Mount Stromlo	7849	100
Potsdam	7841	2000
Sejong	7394	5000
Shanghai	7821	1000
Svetloe	1888	300
Wetzell (SOS)	7827	1000
Zelenchukskaya	1889	300
Zimmerwald	7810	110

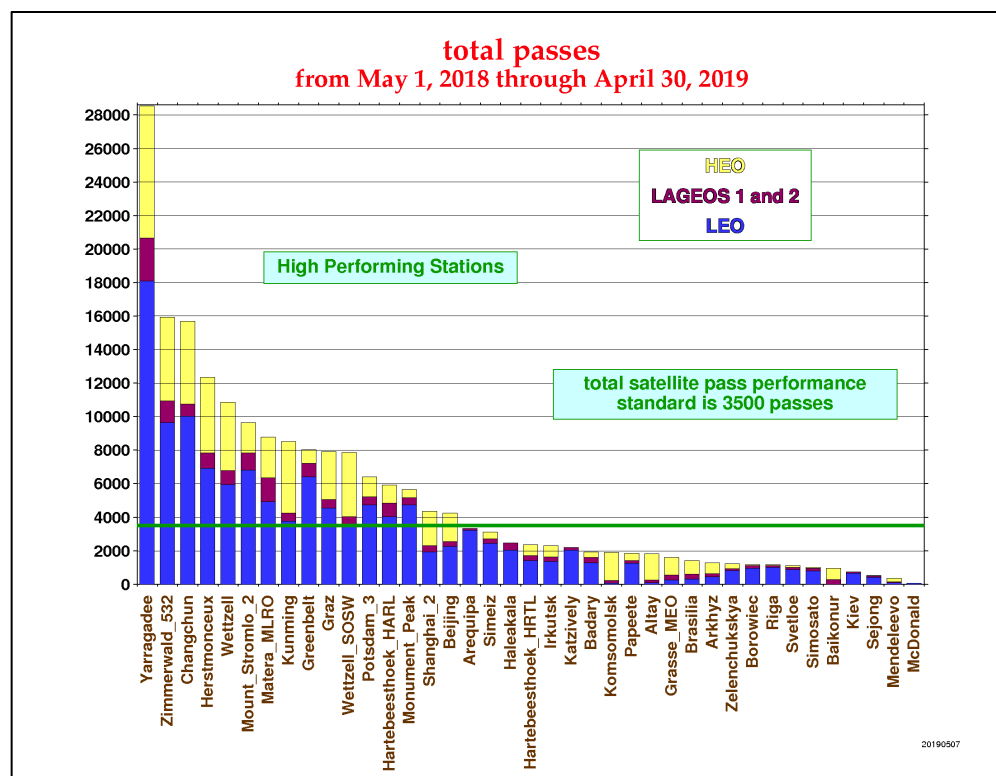


Figure 3. ILRS network performance (total passes), May 2018 through April 2019.

The ILRS assigns satellite priorities in an attempt to maximize data yield on the full satellite complex while at the same time placing greatest emphasis on the most immediate data needs. Priorities provide guidelines for the network stations, but stations may deviate from these priorities to accommodate local conditions, support regional activities or national initiatives, and expand tracking coverage in regions with multiple stations. General tracking priorities are approved by the Governing Board, based on application to the Central Bureau and recommendation of the Missions Standing Committee (see https://ilrs.gsfc.nasa.gov/missions/mission_operations/priorities/index.html).

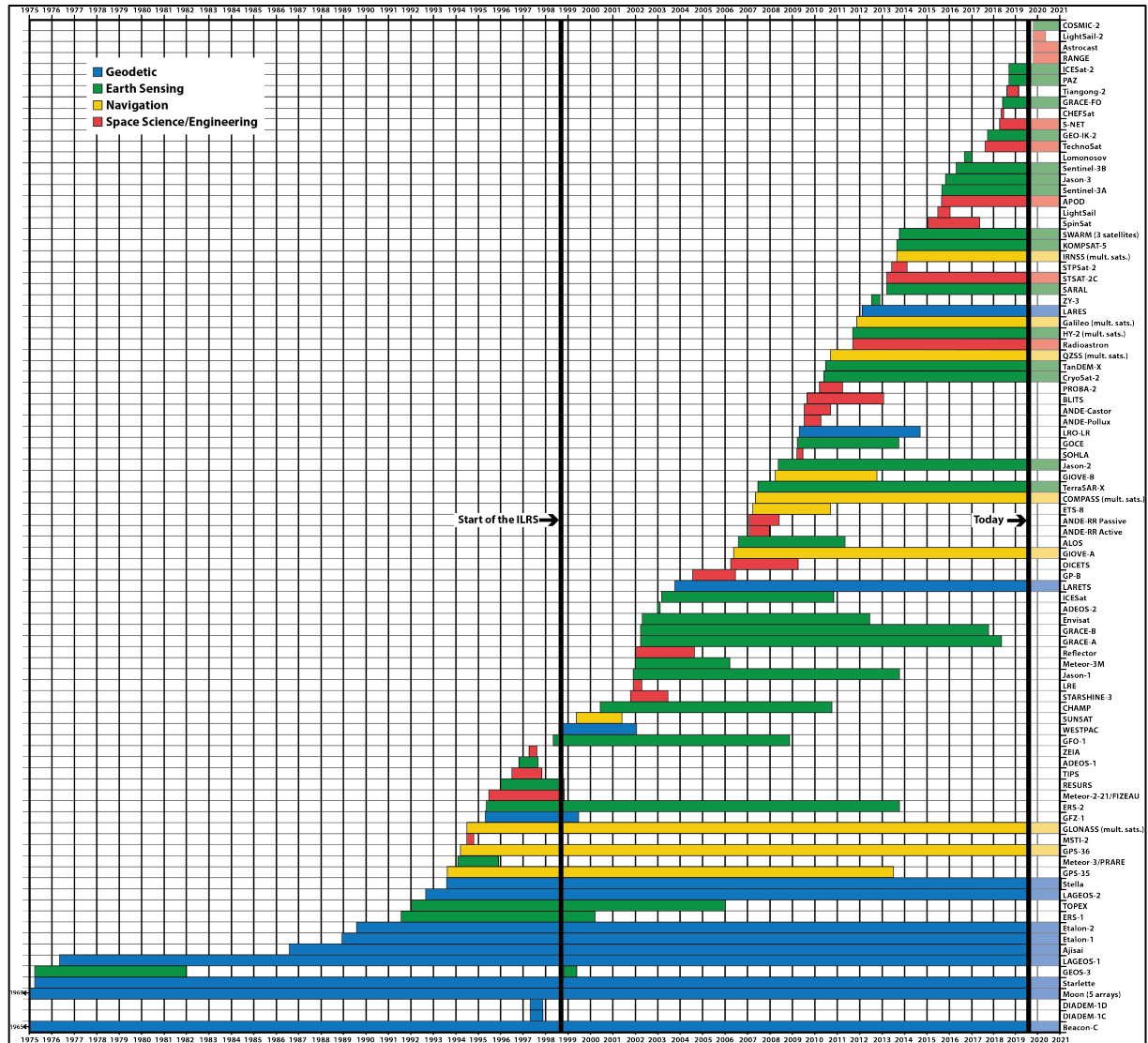


Figure 4. The past, current, and future ILRS satellite tracking list (as of May 2019).

Missions are added to the ILRS tracking roster as new satellites are launched and as new requirements are adopted; missions for completed programs are removed (see Figure 4). Significant effort was spent by the ILRS CB on restricted tracking procedures for the Sentinel-3A and -3B, ICESat-2, and Lomonosov missions to ensure that only authorized stations ranged to the satellites and did so only during authorized time periods to avoid any damage to vulnerable onboard instrumentation. Some stations in the ILRS network continue to track several satellites (e.g., Envisat, TOPEX/Poseidon) considered “space debris” to provide ephemerides and orientation data to help with trajectory/safety planning.

The tracking approval process begins with the submission of a Missions Support Request Form, which is accessible through the ILRS website (https://ilrs.cdis.eosdis.nasa.gov/docs/2016/ilrsmr_1604.pdf).

The form provides the ILRS with the following information: a description of the mission objectives, mission requirements including any tracking restrictions, responsible individuals and contact information, timeline, satellite subsystems, and details of the retroreflector array and its placement on the satellite; a mission concurrence section grants the ILRS stations permission to perform laser ranging to the satellite. This form also outlines the early stages of intensive support that may be required during the initial orbital acquisition and stabilization and spacecraft checkout phases. A list of upcoming space missions that have requested ILRS tracking support is summarized in Table 3 along with their sponsors, intended application, and projected launch dates.

Table 3. Recently Launched and Upcoming Missions (as of May 2019)

Satellite Name	Sponsor	Purpose	Launch Date
Recently Launched			
Compass/BeiDou (10 new, 16 total satellites)	Chinese Defense Ministry	Positioning, navigation, timing	2007- present
Galileo (21 new, 26 total satellites)	ESA	Positioning, navigation, timing	2011- present
GLONASS (5 new, 69 total satellites)	Russian Federation Ministry of Defense	Positioning, navigation, timing	1989-present
IRNSS (4 new, 7 total satellites)	ISRO	Positioning, navigation, timing	2013-2018
QZS (3 new, 4 total satellites)	Cabinet Office, Government of Japan	Positioning, navigation	2017
GRACE-FO-1, -2	NASA, GFZ	Gravity	May-2018
ICESat-2*	NASA	Ice sheet mass balance, sea level	Oct-2018
Jason-3	CNES, NASA, Eumetsat, NOAA	Oceanography	Jan-2016
Lomonosov*	Scobeltsyn Institute of Nuclear Physics, Lomonosov Moscow State University	Upper atmospheric research	Apr-2016
PN-1A	BACC	Precise orbit determination	Sep-2015
Sentinel-3A, -3B*	ESA, Eumetsat	Marine observation	Feb-2016
Approved by ILRS for Future SLR Tracking			
APOD/PN -1B, -1C, -1D	Beijing Aerospace Control Center	Engineering	2015
COSMIC-2	UCAR	Atmospheric research, validation of GNSS orbits	2017
LightSail-B	Planetary Society	Engineering	2017
NISAR	NASA	Earth sensing	2020
Future Satellites with Retroreflectors			
GPS-III	U.S. DoD, DoT	Positioning, navigation, timing	2019
HY-2B, -2C, -2D	CNES, CNSA	Earth observation	2017-2019
LARES-2	ASI, ESA	Relativity, geodesy	2020
Sentinel-6	ESA, Eumetsat, NASA, NOAA	Ocean altimetry	2020
SWOT	NASA, CNES	SAR altimeter	2020

Note: * denotes restricted tracking mission; only authorized stations perform laser ranging to the satellite

During this reporting period, over forty satellites from the GNSS, QZS, and IRNSS constellations were added to the ILRS priority list. In addition, and as shown in Table 3, eight other satellites, including four restricted tracking missions, were launched and supported by the ILRS network. As of May 2019, the ILRS priority list includes eight GLONASS satellites, eight

Compass/BeiDou satellites, eight Galileo satellites, six IRNSS satellites, and four QZS satellite. Predictions are provided for additional GNSS satellites; stations can track these satellites on a non-interference basis with the ILRS priority list satellites.

New ILRS Tracking Strategy for GNSS

During the 18th International Workshop on Laser Ranging in Japan in November 2013, the ILRS agreed to expand network support for GNSS satellites with retroreflector arrays (GLONASS, BeiDou (Compass), Galileo, and eventually GPS. The GLONASS constellation is fully populated. BeiDou and Galileo constellations are in process. GPS satellites with laser retroreflector arrays are now projected to begin deployment in the mid-2020's. There are presently 61 GNSS satellites; when completed, the full GNSS complex should reach over 100 satellites.

User tracking requirements for GNSS fall into two categories: intensive tracking on a small number of satellites in each constellation and sparse sampling on all of the other GNSS satellites. In addition, some users want to schedule focused campaigns for eclipse studies to better model the effects of solar radiation pressure. The ILRS and GGOS formed a joint study group, the LAser Ranging to GNSS s/c Experiment (LARGE) to define an operational tracking strategy to improve ILRS response to user needs. Based on experience from tracking campaigns (See Missions Campaigns below), the new tracking strategy will be:

- GNSS tracking will continued to be prioritized with the other ILRS satellites by the standard ILRS priority scheme (by altitude and inclination);
- Four GNSS satellites can be chosen for intensive tracking by each constellation; all of the remaining GNSS satellites will be relegated to a pool for sparse tracking on a random basis by the stations, with encouragement to support all of the constellations;
- Campaigns will be scheduled to support special requirements (e.g. eclipse coverage).

This new procedure will be announced once the current GNSS tracking campaign are over.

Laser Ranging for High Accuracy Timing

Laser ranging has demonstrated significant capability for Precision Time Transfer with satellites. ILRS tracked the Jason-2 satellite, using the Time Transfer by Laser Link (T2L2) experiment to synchronize the clocks at ILRS stations, as well as to characterize the performance of the DORIS Ultra Stable Oscillator (USO) onboard the Jason-2 spacecraft. The data from T2L2, as well as other information, have been used to derive a detailed model of the DORIS USO behavior, including direct modeling of radiation effects, passage through the South Atlantic Anomaly (SAA) and natural aging of the oscillator. Applying this USO model it was possible to synchronize the clocks used in the Laser Ranging station to the same international time scale (UTC) at around 5 ns accuracy. The analysis of the T2L2 data has revealed that many stations exhibit time biases w.r.t. to UTC, sometimes as high as a few microseconds, well beyond the 200 ns limit requested by the ILRS, and yet still at a level that is hard to resolve from the orbit determination analysis. The past data from T2L2 and data from future similar systems will allow us to characterize station timing behavior and examine its impact on the reference frame and ILRS products. The T2L2 project team led by Dr. Pierre Exertier (Grasse SLR observatory) have provided timing bias estimates for SLR data to the ILRS analysis centers, based on analysis of data from T2L2 over the period 2008-2018.

A precise clock in space provides a worldwide access to high performance ground clocks. Here SLR plays an important role, by providing accurate range and time between clearly defined reference points on ground and in space. This represents a two-way measurement technique, the main ingredient of the “Einstein Synchronization” process, the only technique that can compare remote clocks with high accuracy. The European Space Agency (ESA) is developing

the Atomic Clock Ensemble (ACES) (see <https://earth.esa.int/web/eoportal/satellite-missions/i/iss-aces>) experiment for flight on the International Space Station (ISS). The ELT (European Laser Timing) follows in the path of T2L2. The goal is to demonstrate an accuracy of time transfer at the level of 50 ps, with a perspective of 25 ps. The ELT payload consists of a corner cube retroreflector a SPAD detector, and an event timer. ELT will provide an alternative to time transfer via microwave link (MWL) and will provide superior accuracy.

Lunar Laser Ranging (LLR)

LLR Stations

The LLR results are considered among the most important science return of the Apollo era; it certainly is the only experiment still supporting science. Of all the active ILRS observatories there are currently only four, which are technically in the position to track retro-reflector arrays on the surface of the Moon. These stations are APOLLO (USA), Grasse (France), Matera (Italy) and Wettzell (Germany). New stations are under development in China (Yunnan province), Russia and South Africa. The most active stations during this period (2015-2019) were the Observatoire de la Côte d'Azur, France and the APOLLO site in New Mexico, USA. Since late 2014, the Observatoire de la Côte d'Azur station has ranged primarily in the infrared (1064 nm); these data are available at (<http://www.geoazur.fr>). Unfortunately, the McDonald Observatory in Texas, USA is no longer operational, so its four decade-long time series has been interrupted. New stations are under development in China (Yunnan province), Russia and South Africa. The first LLR experiments were reported from the Yunnan Observatory December 2017 to March 2018. Current resolution is only at the meter level, but upgrading to a short pulse laser is currently planned. System improvements continue at the APOLLO station. Unfortunately, data yield is limited because the telescope is shared with other scientific applications. The station has introduced a novel timing concept to improve ranging stability. Technical improvements have been made at Matera and Wettzell, with noted improvement in performance. At the Altay site in Russia, hardware and software are being introduced, for LLR operation expected to start in the 2021-2022 timeframe.

Although data have been taken on the Apollo 11, 14, and 15, and the Lunokhod 1 and 2 reflectors, the bulk of the data has been from largest reflector on Apollo 15. In the next few years, a new generation of reflectors, more accurate and more efficient, are expected to be deployed on the Lunar surface.

Lunar Analysis Centers

LLR data analysis is carried out by a few major LLR analysis centers: Jet Propulsion Laboratory (JPL), Pasadena, USA; Center for Astrophysics (CfA), Cambridge, USA; Paris Observatory Lunar Analysis Center (POLAC), Paris, France; Institute of Geodesy (IfE), University of Hannover, Germany. In the last few years, the National Institute for Nuclear Physics (INFN), Frascati, Italy, and the Graduate University for Advanced Studies (SOKENDAI), Tokyo, Japan, have also increased their analysis activities. The six LLR analysis centers focus on different research topics (such as relativity, lunar interior, etc.). Some interest towards this end has also been shown by the Hartebeesthoek Radio Astronomy Observatory (South Africa) where an ex-Observatoire de la Côte d'Azur 1-m aperture telescope is being prepared for LLR use. In addition, various research projects have been successfully run combining LLR, GRAIL, and LRO data.

LLR Science

During the last few years, the strong increase in the annual LLR normal point rate was mainly due to the effort at the French station in Grasse (Courde C. et. al., 2017). The total data archive

is still dominated by the Apollo 15 reflector, but its impact was reduced to 69%, and for the period between 2016 and 2018 (Figure 5) the contribution from the smaller reflectors has increased with the Apollo 15 share down to 39%. Data continues to be taken at the APOLLO station but have not been released since 2016; the data statistics for this station shown in Figure 5 were provided through private communication and not reflected in Figures 6-8.

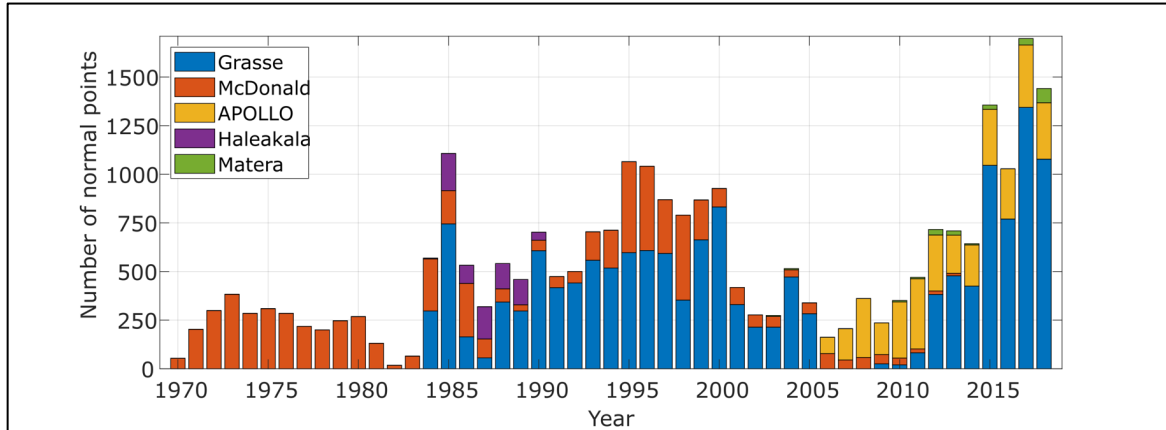


Figure 5. Distribution of LLR normal points taken by the major observatories over the years

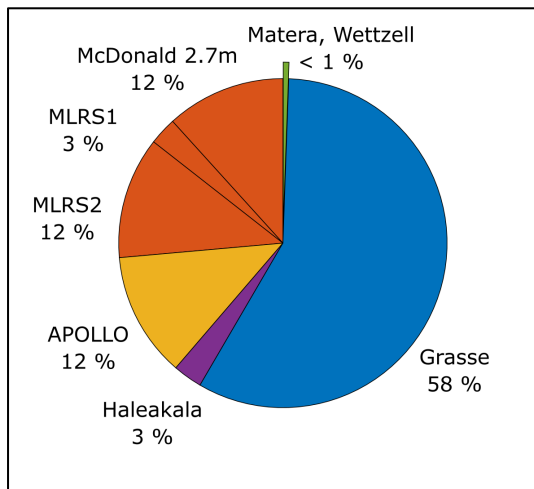


Figure 6. Measurement statistics (1970-2018) by station.

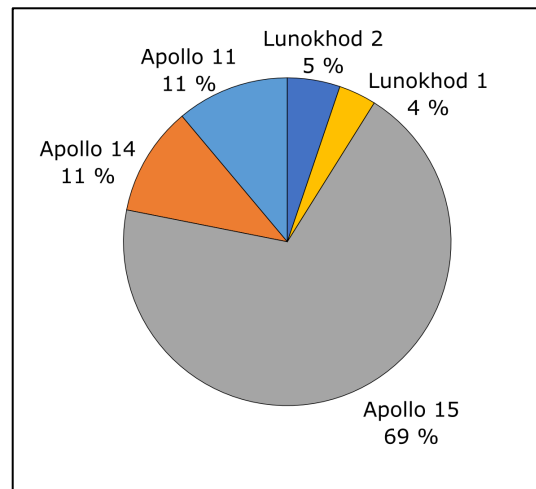


Figure 7. Measurement statistics (1970-2018) by reflector.

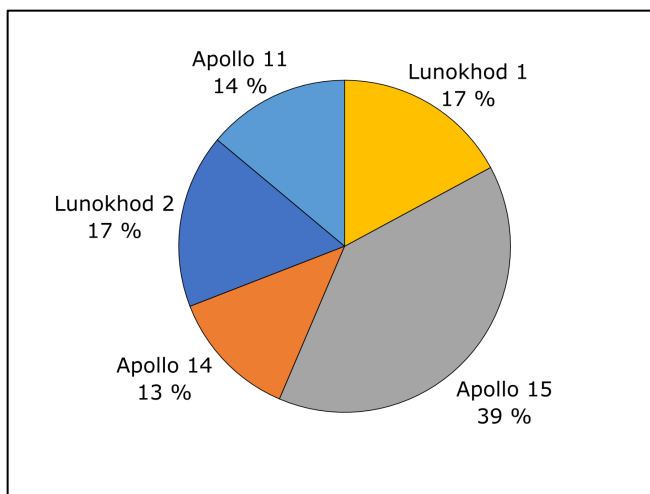


Figure 8. Measurement statistics (2016-2018) by reflector.

LLR is an important tool to support lunar science, to study the Earth-Moon dynamics and to test General Relativity in the solar system. Current improvements in the estimation of relativistic parameters include, e.g., tests of the equivalence principle, possible time variability of the gravitational constant and Lorentz symmetry (Hofmann F. and Müller J., 2018). LLR

based EOP results contribute to combined EOP solutions. With the larger LLR data set over time [9], the lunar tidal acceleration has been more accurately determined (Williams J.G. and Boggs, D.H., 2016) as well as station coordinates and velocities. Through the studied of lunar tides, physical librations and the lunar orbit, LLR is been an important tool in improving our understanding of the physical properties and the interior of the Moon. Discrepancies between LLR and GRAIL derived results (Pavlov, D.A. et. al, and 2016) of elasticity parameters (Love numbers) and the degree 3 gravitational field which leads us to recognize that there is still very interesting and challenging science to address, especially in the modelling of dissipation and properties of the lunar interior.

The LLR community is growing with new stations and new analysis centers. In the next few years, a new generation of reflectors, more accurate and more efficient, are expected to be deployed on the Lunar surface. LLR again has shown is strong capability to put Einstein's relativity theory to test and to improve the limits for a number of relativistic parameters. Also, lunar science and many quantities of the Earth-Moon dynamics could widely be studied. As the next step, a new structure in ILRS (e.g., a working group or standing committee) shall be created to link all LLR contributors, from observatories to science.

Recent Activities

General

The ILRS Governing Board approved an update to the ILRS Terms of Reference (ToR) (<https://ilrs.gsfc.nasa.gov/about/termsoref.html>) in mid-2016; the IAG accepted the revision and the new Terms of Reference (ToR) was adopted in November 2016. The most significant change to the ILRS ToR was the addition of two At-Large members to the ILRS GB who will be appointed by the GB. Other changes addressed the addition of new SCs and clarifying terminology.

Standing Committee and Study Group Activities

All ILRS standing committees held meetings during ILRS workshops held during the reporting period (2015 ILRS Technical Workshop in Matera Italy and the 20th International Workshop on Laser Ranging in Potsdam Germany). The Analysis SC held additional meetings during the 2015, 2016, and 2017 EGU General Assemblies in Vienna Austria.

Analysis Standing Committee (ASC)

In addition to the production of the official ILRS ASC products, the ASC focused on two Pilot Projects (PP) during the reporting period: one was a continuation of the orbital product PP, which in early 2016 evolved into a bona fide official product as reported earlier under the "Data Products" section. The other PP was agreed at the ILRS Tech. Workshop in Matera, Italy, and the purpose of that effort was to develop a robust and efficient analysis procedure that will monitor the long-term performance of systematic errors at stations. A test period of four years (2005 to end of 2008) was selected for the validation of the procedure and the products of the contributing ACs. Of the eight ACs, six contributed to the PP. In the initial phase a combination of all available contributions was performed and the comparison of the individual estimates to the combined result was used to validate the contributing series. In the next phase of the PP the ACs reanalyzed all LAGEOS, LAGEOS-2 and Etalon-1 and -2 SLR data from 1993 to end of 2018 and generated a complete series of weekly estimates of biases for all systems. In the final step we will examine these biases on a system by system basis and aggregate them in groups that show a stable mean over time. These biases will be adopted as "a bias to be applied a priori" in the future reanalysis for the ITRF. The procedure will be implemented as the standard in our operations and the ASC will develop guidelines for identifying likely errors and notify the

affected stations. This step is expected to be completed before the end of 2019. Another PP in progress is the introduction of LARES as the fifth target to be used for the development of the official ILRS products and at the same time, the delivery of weekly averaged low-degree spherical harmonic coefficients of the gravitational field model. This PP is expected to be completed by the end of 2019.

Based on simulation studies that indicated the role that increased Etalon 1 & 2 data could play in the enhancement of ILRS EOP products (Andritsch, in press), the ASC called for an intensive tracking campaign that was held from February 15 to May 15, 2019. The amount of range data (NPs) that was collected nearly doubled from that over the same period a year ago. The ASC will further evaluate the effect of these additional data on the EOP products and make appropriate recommendations to the ILRS CB.

The co-chairs of the ASC are acting as guest-editors the publication of a special issue of the Journal of Geodesy, dedicated on Laser Ranging. The call-for-submissions resulted in over forty proposed contributions. As of this writing there are twelve articles accepted and another twelve still under the review process.

Data Formats and Procedures Standing Committee (DFPSC)

The DFPSC, especially the “Data Format Update” study group, worked on the review and update of the ILRS standard CRD (data) and CPF (prediction) formats. This was necessary in order to fulfill the needs of the European Laser Timing Experiment (ELT) but also for debris tracking. Additionally, the extension of the CRD and CPF formats was also required in order to provide additional information about meteorology, software, camera, calibration, predictions, etc. within the data. 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 online on the EDC website. A similar manager was created for the station history log. Both are now in operation, and the ILRS website has been updated with information on the new procedures.

The inconsistent handling of the leap second in the prediction files and at the station led to difficulties in acquiring data during the time around leap seconds. Therefore, the DFPSC formulated a new procedure which proposed to stop tracking during leap seconds.

The ILRS operates two global data and operation centers. In order to achieve homogeneous data centers, the applied quality checks by the OCs have to be identical. Work is nearly complete on this task, which includes a detailed check of the CRD data fields for reasonable values.

Missions Standing Committee (MSC)

The MSC, working with the ILRS CB, completed a revision to the ILRS Missions Support Request form. This form is the vehicle used by mission sponsors to provide information required by the ILRS to enable the ILRS to determine if future laser ranging to the satellite is warranted. The form provides key contacts and parameters to allow the ILRS to use the SLR data in the development of science data products and to provide the missions with SLR data that supports their goals. The MSC also reviewed submitted request forms and provided recommendations and feedback to the CB and GB for future mission support. The ILRS now requests the form should be submitted at least 6 months prior to launch or from when missions expect tracking support to begin. Missions approved during the reporting period include: COSMIC-2, LightSail-B, Lomonosov, NISAR, Sentinel-3A/-3B, TechnoSat, ICESat-2, S-NET, GRACE Follow-On, GEO-IK-2, RANGE, CHEFSat, Tiangong-2, HY-2B, QZS, Beidou, PAZ and Astrocass Precursor.

Networks and Engineering Standing Committee (NESC)

The SSG works to identify existing software of use to ILRS stations. The SSG has worked with the ILRS CB to provide links to these software packages on the ILRS website. A set of lunar prediction, filtering, and normal pointing software has been added to the software available on the website. Also, an SLR normal pointing program has been added and is available for testing and implementation. A program showing sky plots of available satellites from any given station is another package now accessible from the ILRS website. Updated sample software for the new version 2 of the CPF and CRD formats is now available.

Transponders Standing Committee (TSC)

Currently, the main focus for the TSC is on highly accurate time transfer, particularly ELT for ACES (expected launch in 2018) on the International Space Station. The SC is working with stations to implement requirements for the mission. During its meetings, the SC also discussed common view time transfer and cross system ranging via space debris targets for the direct detection of the laser return and diffusely scattered signal from the partner station. Experiments are underway.

Quality Control Board (QCB)

The ILRS Quality Control Board was organized at the 19th International Workshop on Laser Ranging to address SLR system biases and other data issues that have degraded the ILRS data and their derived products. The board is a joint activity under the ASC and the NESC and meets by telecon on a bimonthly basis. Current activities include reviewing the results from the ASC's "Station Systematic Error Monitoring Pilot Project" and the development of tools for the stations to view system performance and examine systematic errors. Several of these tools are now available to the users, with the intention to have the complete ensemble of these web-based diagnostic tools online by the latter part of 2019. Four ACs have been routinely examining the incoming SLR data and providing rapid feedback to the stations on suspect performance using the "Rapid Response" exploder (Otsubo et al., 2018). The Board is also evaluating tools and procedures that would enhance data scrutiny at the stations.

Software Study Group (SSG)

The SSG works to identify existing software of use to ILRS stations. The SSG has worked with the ILRS CB to provide links to these software packages on the ILRS website. A set of lunar prediction, filtering, and normal pointing software has been added to the software available on the website. Also, an SLR normal pointing program has been added and is available for testing and implementation. A program showing sky plots of available satellites from any given station is another package now accessible from the ILRS website. Updated sample software for the new version 2 of the CPF and CRD formats is now available.

Space Debris Study Group (SDSG)

The SDSG was formed in 2014 to coordinate and assist stations in laser ranging to space debris targets. The SG also acts as an interface between the ILRS and the space debris activities within ESA. Early on, the SG organized several campaigns on TOPEX, Envisat, and other SD targets. Over the last three years, the number of stations tracking space debris has increased significantly. Measurements in multi-static/bi-color debris ranging measurements are being taken to uncooperative targets. "Stare and Chase" is another method for tracking uncooperative targets and has also been successfully tested. Significant results have been seen for science, POD, attitude motion, pre-entry data, and other applications. Work continues to extend debris laser ranging time into full daylight and during full night.

A dedicated server has been set up in Graz, where stations can deposit their laser ranging data from space debris targets; stations can also use this server to download updated CPF/TLE files for space debris targets.

Mission Campaigns

LARGE

Several GNSS tracking campaigns have been held since 2014, testing different combinations of satellite selections and priorities. Some improvement has been seen, but it may also have been the result of stations becoming more familiar with GNSS tracking procedures. Details on early campaigns can be found in a poster presented at the 2015 ILRS Technical Workshop in Matera (Noll et al., 2015).

In 2018, the ILRS conducted two LARGE tracking campaigns to examine how the service might strike a balance between the GNSS user needs and still maintain the priorities of lower altitude satellites. In each campaign, a short list of GNSS satellites was identified by the GNSS constellations for high intensity tracking (3 segments per pass), higher priority tracking in the current GNSS priority band. A larger pool of lower priority GNSS satellites was identified for sparse tracking (1 segment per pass) by the stations on an “as time available” basis. The campaigns demonstrated that the network could support this kind of strategy, with the intensive coverage hopefully increasing over time. Results from the 2018 LARGE campaigns can be found in the monthly reports section available on the ILRS website. Based on the results from the campaigns and discussions with the IGS, a new tracking strategy is being implemented (see Section on *New GNSS Tracking Strategy* above).

In the meantime, a three-week (May 15 through June 5, 2019) high intensive tracking campaign has been undertaken with many of the high performing network stations to monitor the orbits of Galileo-102 and -220 as they go through a series of eclipse conditions over Europe.

GREAT

Monthly campaigns were conducted on Galileo-201 with Galileo-202 as a backup, to study the behavior of on-board clocks and the gravitational redshift predicted by General Relativity. Launch problems placed in elliptical orbits which induced a periodic modulation of the gravitational redshift at the orbital frequency. In response to a Galileo mission request, the ILRS conducted monthly, week-long campaigns for a period of one year in support of the Galileo gravitational Redshift Experiment with eccentric sATellites (GREAT) experiment.

In addition to the LARGE and GREAT efforts, the ILRS has supported several other tracking campaigns, including the IRNSS constellation at geosynchronous orbits.

ILRS Meetings

The ILRS organizes yearly workshops, the biannual International Workshop on Laser Ranging and then ILRS Technical Workshops, oriented toward SLR practitioners, on the years between. Meetings of the Governing Board and standing committees are typically held in conjunction with these ILRS workshops. A summary of recent and planned ILRS meetings is shown in Table 4. Minutes and presentations from the workshops and these splinter meetings are available from the ILRS website (<https://ilrs.gsfc.nasa.gov/about/reports/workshop/index.html> and https://ilrs.gsfc.nasa.gov/about/reports/meeting_reports.html).

The ILRS also conducts meetings of the Central Bureau on a monthly basis. These meetings review network station operation and performance, as well as coordinate support of upcoming missions, monitoring and managing the ILRS infrastructure, and future directions and activities.

In May 2016, the ILRS celebrated forty years of supporting LAGEOS; the satellite was launched on May 04, 1976. To acknowledge the anniversary, the NASA Space Geodesy Program sponsored a symposium at NASA GSFC with several talks from speakers involved in the program over the last forty years. Links to information about the symposium as well as general information about LAGEOS, is available at the website: https://lageos.cddis.eosdis.nasa.gov/Celebrating_40_years_of_LAGEOS.html. Similarly, 30 years of Ajisai tracking was celebrated on August 13, 1986.

Table 4. Recent ILRS Meetings (as of May 2019)

Timeframe	Location	Meeting
April 2015	Vienna, Austria	ILRS Analysis Standing Committee meeting
October 2015	Matera, Italy	2015 ILRS Technical Workshop ILRS Governing Board meeting ILRS Standing Committee meetings
October 2016	Potsdam, Germany	20 th International Workshop on Laser Ranging ILRS Governing Board meeting ILRS Standing Committee meetings
April 2016	Vienna, Austria	ILRS Analysis Standing Committee meeting
April 2017	Vienna, Austria	ILRS Analysis Standing Committee meeting
October 2017	Riga, Latvia	2017 ILRS Technical Workshop ILRS Governing Board meeting ILRS Standing Committee meetings
April 2018	Vienna, Austria	ILRS Analysis Standing Committee meeting
November 2018	Canberra, Australia	21 st International Workshop on Laser Ranging ILRS Governing Board meeting ILRS Standing Committee/Study Group meetings
April 2019	Vienna, Austria	ILRS Analysis Standing Committee meeting

The ILRS co-sponsored several workshops over the last five years. These workshops include the bi-annual International Workshop on Laser Ranging which covers a wide range of topics throughout the service including scientific, engineering, mission, and infrastructure presentations. In addition, in recent years, the ILRS has conducted Technical 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.

The 2015 ILRS Technical Workshop was held in October 2015 in Matera Italy; the theme of the focused workshop was “Network Performance and Future Expectations for ILRS Support of GNSS, Time Transfer, and Space Debris Tracking” and address the topics that impact the quality of the data products and operations. Abstracts, presentations, posters, and papers from the workshop are online at the workshop’s website: https://cddis.nasa.gov/2015_Technical_Workshop/.

In October 2016, the Helmholtz Center Potsdam of the GFZ German Research Centre for Geosciences organized and hosted the 20th International Workshop on Laser Ranging in Potsdam, Germany. Over 170 attendees participated in the workshop. 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 and science; workshop materials, abstracts, presentations, posters, and papers, are available at the meeting’s website <https://cddis.nasa.gov/lw20>. This workshop continued the “station clinic” session concept to address station operations topics; ILRS experts met in small groups of station engineers and operators to provide solutions to common station problems, information to maintain station stability, and guidelines for interacting with the analysts in determining station biases.

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 2-5, with the theme "Improving ILRS Performance to Meet Future GGOS Requirements". Over 120 people from 21 countries participated in the meeting. The program included over 50 oral presentations, as well as many relevant posters.

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" afforded presentations on a wide range of topics highlighting SLR contributions to research. 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, which has synergy with new ILRS applications. Over 175 registrants 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; these presentations, posters, and resulting papers are available on the proceedings website at <https://cdsis.nasa.gov/lw21>.

Publications

Detailed reports from past meetings can be found on the ILRS website. ILRS Biannual Reports summarize activities within the service over the period since the previous release. They are available as hard copy from the CB or online at the ILRS website. The latest volume is the eighth published report for the ILRS and concentrated on achievements and work in progress rather than ILRS organizational elements. However, this report, the 2009-2010 ILRS Report, published in late 2012, was the last edition produced by the ILRS due to the extensive amount of work required to generate these documents. The ILRS CB is currently working with the ILRS components to prepare the next service report to cover 2016-2018.

The ILRS Central Bureau continues to maintain the ILRS website, installed on a CDDIS webserver at NASA GSFC. The website, <https://ilrs.gsfc.nasa.gov>, is updated several times per week as required. A bibliography of laser ranging publications is maintained on this website.

ILRS Analysis Center reports and inputs are used by the Central Bureau for review of station performance and to provide feedback to the stations when necessary. Special weekly reports on on-going campaigns are issued by email. The CB also generates monthly and quarterly Performance Report Cards and posts them on the ILRS website (https://ilrs.gsfc.nasa.gov/network/system_performance/index.html). These Report Cards evaluate data quantity, data quality, and operational compliance for each tracking station relative to ILRS minimum performance standards. These results include independent assessments of station performance from several of the ILRS analysis/associate analysis centers. The statistics are presented in tabular form by station and sorted by total passes in descending order. Plots of data volume (passes, normal points, and minutes of data) and RMS (LAGEOS, Starlette, calibration) are created from this information and available on the ILRS website. Plots, updated frequently, of multiple satellite normal point RMS and number of full-rate points per normal point as a function of local time and range have been added to the ILRS website station pages.

Issues and Challenges

Several challenges are on the horizon for the ILRS as it moves forward. Some of the new stations underway and planned will help address geographic gaps in the network, but many gaps remain, primarily in Latin America, Africa, and Oceania. The ILRS network still consists of a mix of new and old technologies and levels of financial support, and the lack of standardization in system hardware and operations introduces data issues that require attentions. The number of satellite targets, particularly in the GNSS constellations, continues to increase. The ILRS is implementing a new GNSS tracking strategy (see sections on Satellite Missions) to address the increase in the number of GNSS satellites and the increase in user requirements. The Furthermore, there is a need to be more selective on the time spent on each target. Data quality issues continue to affect the ILRS products; rapid data review feedback to the stations continues to improve and on-line data evaluation software tools have been implemented. The progress made in the improvement of the geodetic satellite center of mass corrections has been significant and incipient data bias sources, particularly in calibration area.

References

- Andritsch, F., A. Grahl, R. Dach, T. Schildknecht and Adrian Jäggi (2019) “Simulation of tracking scenarios to LAGEOS and Etalon Satellites”, *J Geod* (2019), (in press).
- Courde C., Torre J-M, Samain E., Martinot-Lagarde G., Aimar M., Albanese D, Exertier P, Fienga A, Marley H, Metris G, Viot H, Viswanathan V (2017) Lunar laser ranging in infrared at the Grasse laser station. *Astron. Astrophys.* 602:A90, DOI 10.1051/0004-6361/201628590
- Hofmann F., Müller J. (2018) Relativistic tests with Lunar Laser Ranging, *Classic and Quantum Gravity.* 35:035015, DOI 10.1088/1361-6382/aa8f7a
- Luceri, V., E. C. Pavlis, B. Pace, D. König, M. Kuzmicz-Cieslak, G. Bianco, (2014), “Overview of the ILRS contribution to the development of ITRF2013”, *IAG Geodesy Symposia, Proceedings of REFAG2014*, T. van Dam (Ed.), Springer.
- Müller, J., L. Biskupek, F. Hofmann, E. Mai, (2014) “Lunar Laser Ranging and Relativity”. Book chapter in “*Frontiers of Relativistic Celestial Mechanics*”, vol. 2 (ed. by S. Kopeikin), de Gruyter, p. 99-146, 2014.
- Noll, C., M. Pearlman, M. Torrence, (2015) “Summary of Results from ILRS GNSS Tracking Campaigns”, presented at 2015 ILRS Technical Workshop, Matera, Italy, October 26-30, 2015.
(https://cdis.nasa.gov/2015_Technical_Workshop/docs/posters/P1.8_Noll_poster.pdf).
- Otsubo, T., Müller, H., Pavlis, E.C. et al. *J Geod* (2018) “Rapid response quality control service for the laser ranging tracking network”, <https://doi.org/10.1007/s00190-018-1197-0>
- Pavlis, E. C., V. Luceri, M. Kuzmicz-Cieslak, D. König, G. Bianco, (2014), “Modeling improvements in the ILRS reprocessing for ITRF2013”, presented at the IAG Geodesy Symposium REFAG2014, 12-17 October, 2014, Luxembourg, (http://geophy.uni.lu/users/tonie.vandam/REFAG2014/SESS_II_Techniques/Pavlis_.pdf).
- Pavlis, E. C., G. Sindoni, Ciufolini, I. A. Paolozzi, (2015) “Contribution of LARES and geodetic satellites on Environmental monitoring”, *Proceedings of 15th Inter. Conf. on Environment and Electrical Engineering*, 10-13 June, 2015, Rome, Italy, (<https://easychair.org/conferences/submission.cgi?submission=2290027;a=8709951>).

Pavlov D.A., Williams J.G., Suvorkin V.V. (2016) Determining parameters of Moon's orbital and rotational motion from LLR observations using GRAIL and IERS-recommended models. *Celest. Mech. Dyn. Astron.* 126:61–88, DOI 10.1007/s10569-016-9712-1

Williams J.G., Boggs D.H. (2015) Tides on the Moon: Theory and determination of dissipation. *J. Geophys. Res. (Planets)* 120:689–724, DOI 10.1002/2014JE004755