

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 will need to significantly improve the quantity and quality of ranging to the geodetic constellation (LAGEOS-1, LAGEOS-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

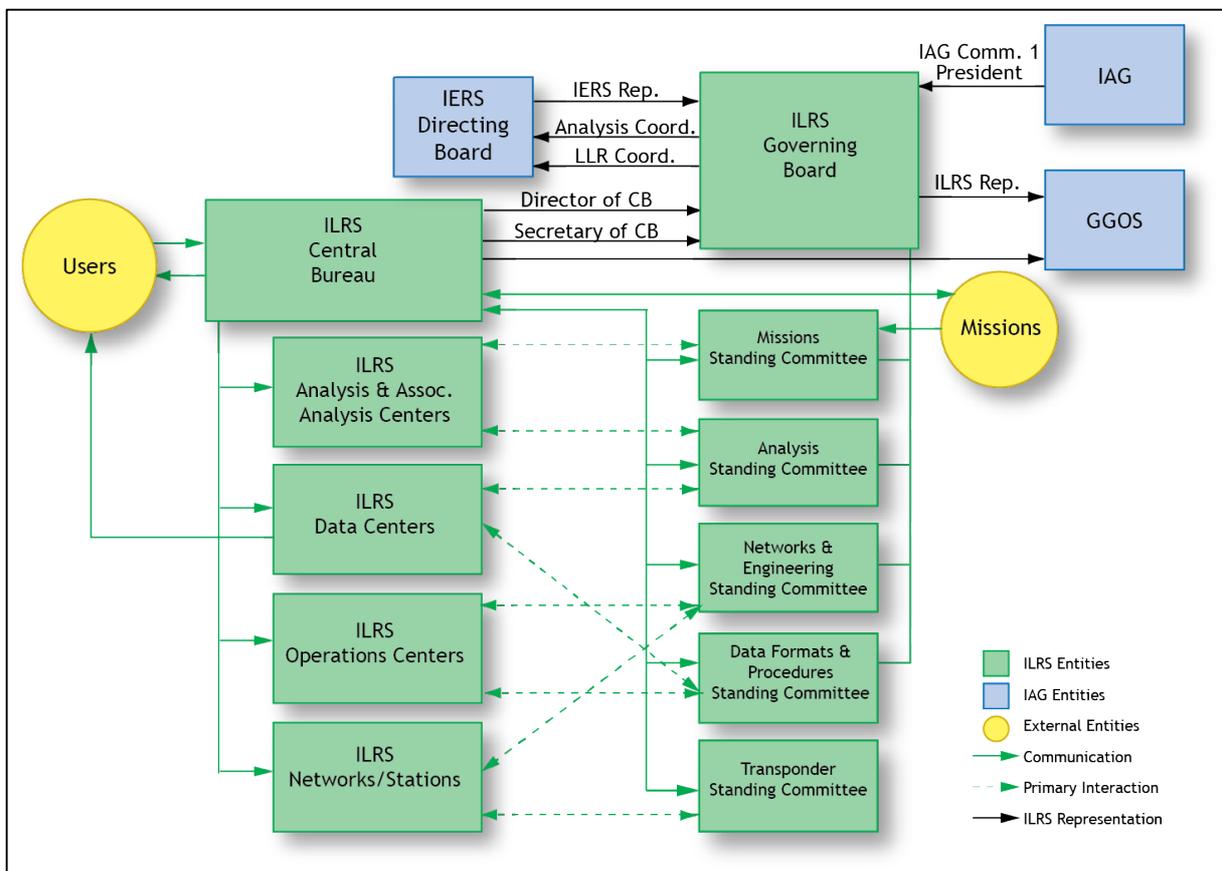


Figure 1. The organization of the International Laser Ranging Service (ILRS).

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.

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.

Table 1. ILRS Governing Board (as of May 2017)

Name	Position	Country
James Bennett	Appointed, WPLTN	Australia
Giuseppe Bianco	Appointed, EUROLAS, Governing Board Chair	Italy
Ludwig Combrinck	Elected, Lunar Representative	South Africa
Urs Hugentobler	Ex-Officio, Representative of IAG Commission 1	Germany
Georg Kirchner	Appointed, EUROLAS, Networks and Engineering Standing Committee Co-Chair	Austria
Vincenza Luceri	Elected, Analysis Representative, Analysis Standing Committee Deputy Chair	Italy
David McCormick	Appointed, NASA	USA
Jan McGarry	Appointed, NASA, Transponder Standing Committee Co-Chair	USA
Horst Mueller	Elected, Data Centers Representative, Data Formats and Procedures Standing Committee Chair	Germany
Carey Noll	Ex-Officio, Secretary, ILRS Central Bureau	USA
Toshimichi Otsubo	Appointed, WPLTN, Missions Standing Committee Chair	Japan
Erricos Pavlis	Elected, Analysis Representative, Analysis Standing Committee Chair	USA
Michael Pearlman	Ex-Officio, Director, ILRS Central Bureau	USA
Ulrich Schreiber	Elected, At-Large, Transponder Standing Committee Chair	Germany
Daniela Thaller	Appointed, IERS Representative to ILRS	Germany
Matt Wilkinson	Elected, At-Large, Networks and Engineering Standing Committee Chair	UK
TBN	Appointed, At-Large	
TBN	Appointed, At-Large	
Former Governing Board Members during 2015-2017		
Wu Bin	Appointed, WPLTN	China
Jürgen Müller	Elected, Lunar Representative	Germany

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
- 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 through a pilot project. 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 plans to issue an extended version of the reference frame, the SLRF2017, which will include some two-dozen additional SLR sites that were not part of ITRF2014. The ASC will re-analyze all of the data received since 1983, using the new ITRF and new models for an improved standard product that are consistent with the currently released operational products. 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.

Currently, the LLR group is in the process of developing a unique data set of all available LLR data in the newly adopted CRD format, in order to better serve the community and to conform with the ILRS standards.

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 (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 an SLR station with the NASA MOBLAS at Hartebeesthoek (South Africa) and have offered to place a system in Tahiti co-located with the NASA systems there. The Russians are also planning the installation of a new system in Ensenada (Mexico). The TIGO system, operational in Concepción (Chile) since 2002, was closed in 2014 and relocated to La Plata (Argentina); operations are expected to resume in late 2017. New stations, underway at Ponmundi and Mt. Abu (India) and in Metsahövi (Finland) are expected to be operational in late 2017 or early 2018. A new SLR station is planned for Yebes (Spain). The NASA Space Geodesy Project (SGP) is planning for construction of up to ten next generation SLR systems as part of core sites; the first of those systems are planned for deployment at McDonald, TX, Haleakala, HI and GSFC in the 2019–2021 timeframe. A fourth is being built in cooperation with the NMA for Ny Ålesund (Norway). Several systems are planned to replace current legacy systems. 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 each LAGEOS satellite (600 LAGEOS passes per year)
- 2 passes per week on each HEO satellite (>3000 HEO passes per year)

In general, stations continue to improve their performance. Several stations dominated the network in the last three years, with the Yarragadee, Changchun and Mt. Stromlo stations being the strongest performers. The next group of stations with impressive contributions included Herstmonceux, Graz, Wettzell, Greenbelt, Zimmerwald, Monument Peak, Matera, and Potsdam. During the twelve-month period from April 2016 to March 2017, thirteen stations met the updated ILRS minimum requirement for total numbers of passes tracked (see Figure 3).

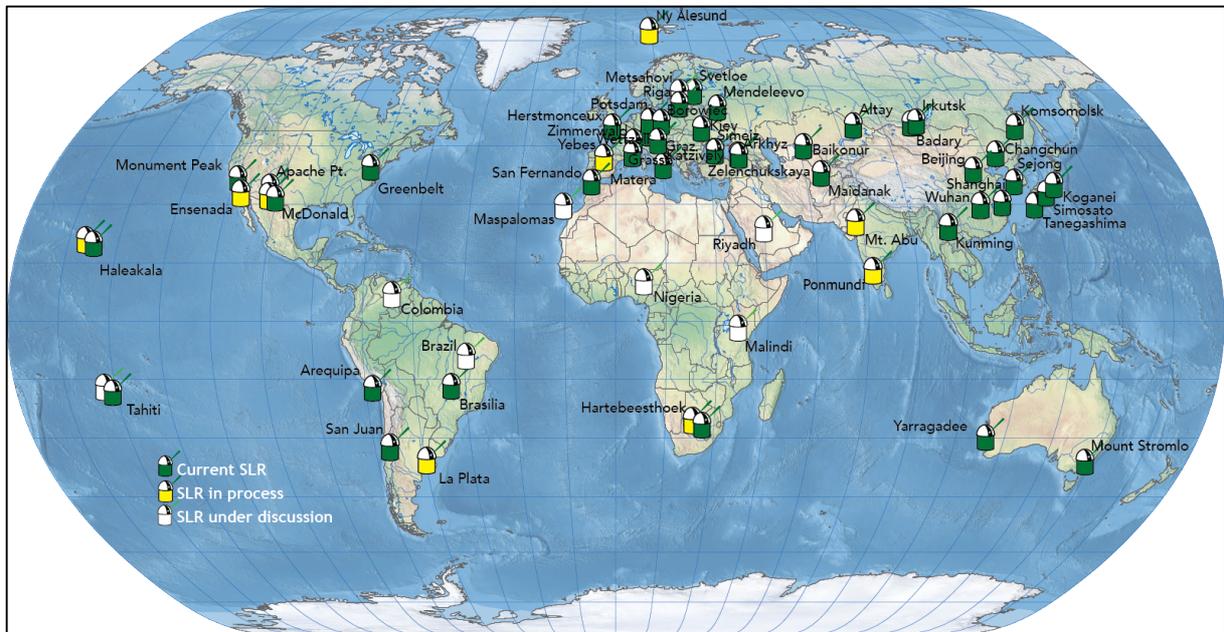


Figure 2. ILRS network (as of May 2017).

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. 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 over ninety artificial satellites including passive geodetic (geodynamics) satellites, Earth remote sensing satellites, navigation satellites, 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. 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.

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 occasionally deviate from the priorities to support regional activities or national initiatives and to expand tracking coverage in regions with multiple stations. General tracking priorities are set 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).

Table 2. High-Repetition Rate ILRS Stations (as of May 2017)

Site Name	Station	Repetition Rate (Hz)
Altay	1879	300
Arkhyz	1886	300
Badary	1890	300
Baikonur	1887	300
Beijing	7249	1000
Brasilia	7407	300
Changchun	7237	1000
Graz	7839	2000
Herstmonceaux	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
Wettzell (SOS)	7827	1000
Zelenchukskaya	1889	300
Zimmerwald	7810	110

Total Passes
(from April 1, 2016 through March 31, 2017)

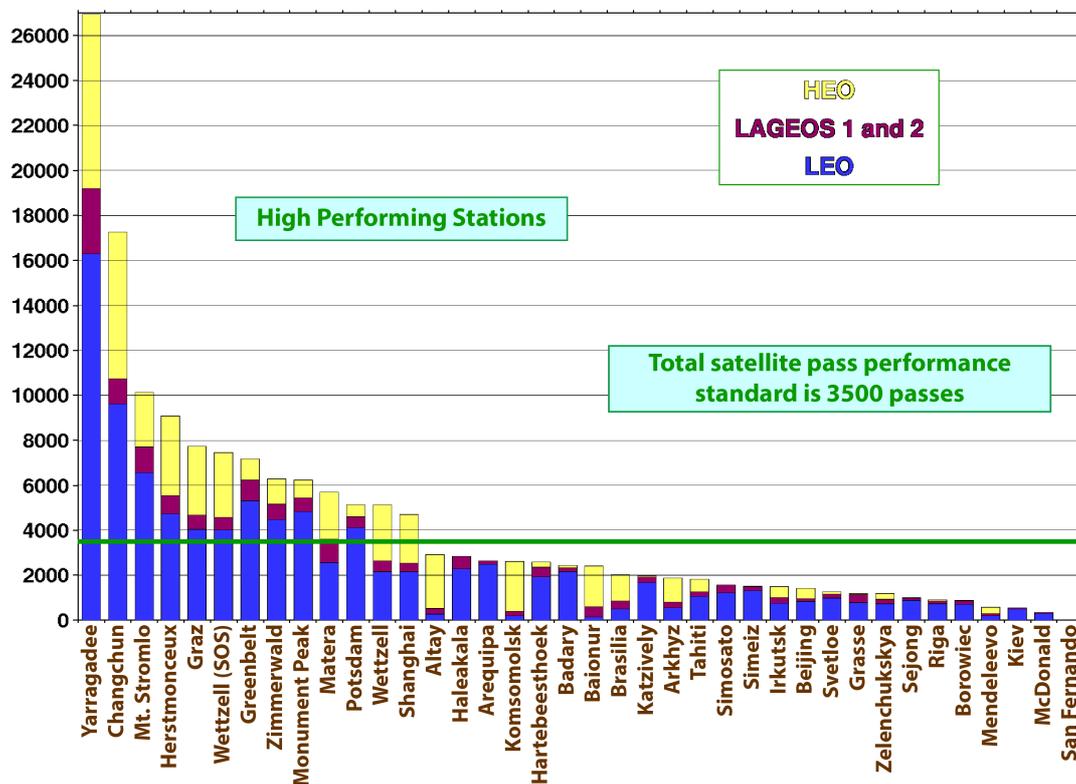


Figure 3. ILRS network performance (total passes), April 2016 through March 2017.

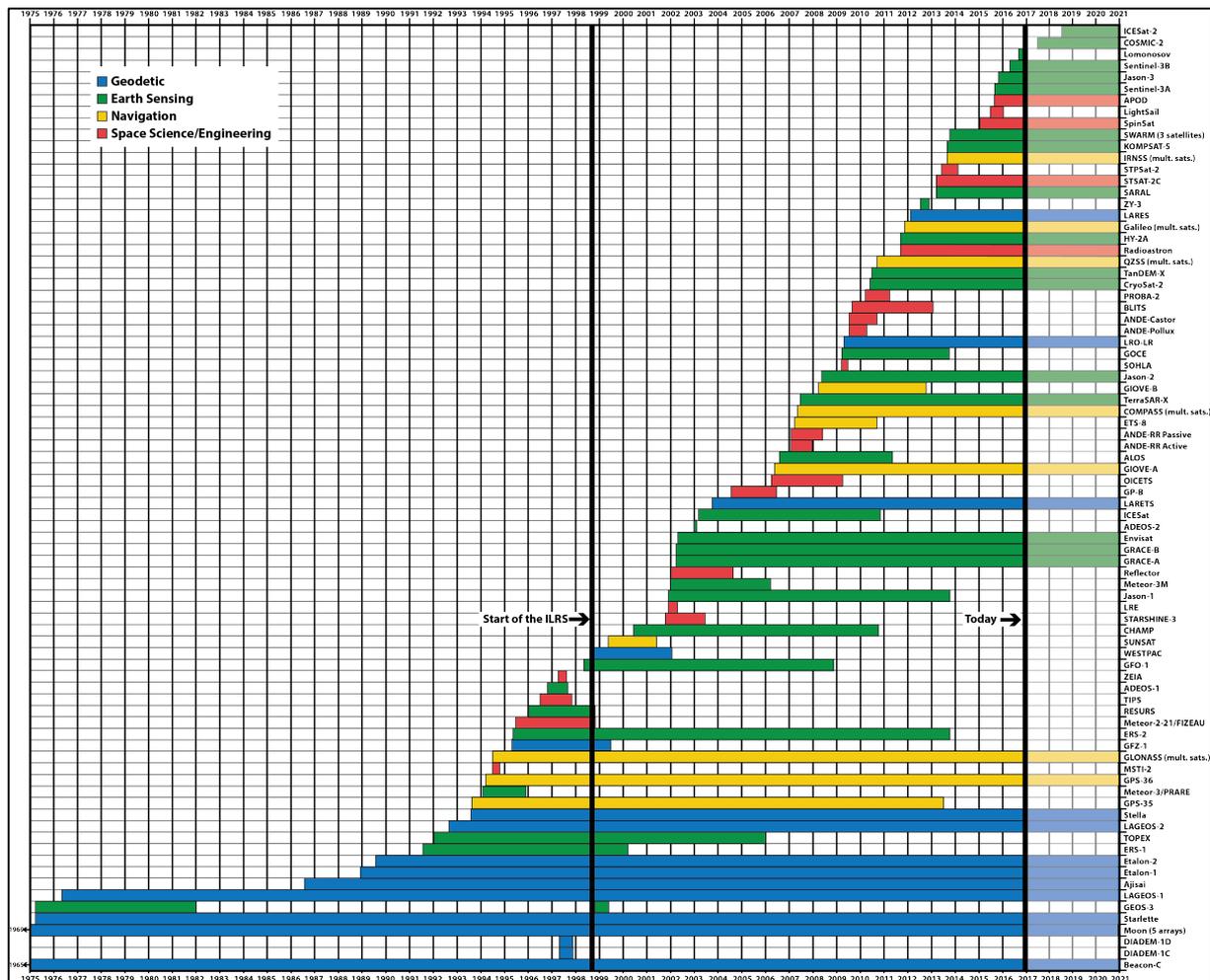


Figure 4. The past, current, and future ILRS satellite tracking list (as of May 2017).

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 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. The ILRS continues to track several satellites (e.g., Envisat, TOPEX/Poseidon, ETS-8) 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.cddis.eosdis.nasa.gov/docs/2016/ilrmsr_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 2 along with their sponsors, intended application, and projected launch dates.

Table 2. Recently Launched and Upcoming Missions (as of May 2017)

Satellite Name	Sponsor	Purpose	Launch Date
Recently Launched			
Compass (5 new, 9 total satellites)	Chinese Defense Ministry	Positioning, navigation, timing	2007- present
Galileo (13 new, 18 total satellites)	ESA	Positioning, navigation, timing	2011- present
GLONASS (2 new, 24 total satellites)	Russian Federation Ministry of Defense	Positioning, navigation, timing	1989-present
IRNSS (3 new, 6 total satellites)	ISRO	Positioning, navigation, timing	2013-2016
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*	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
QZS-2, -3, -4	Cabinet Office, Government of Japan	Positioning, navigation	2017
Sentinel-3B	ESA, Eumetsat	Oceanography	2017
Future Satellites with Retroreflectors			
GPS-III	U.S. DoD, DoT	Positioning, navigation, timing	2019
HY-2B, -2C, -2D	CNES, CNSA	Earth observation	2017-2019
ICESat-2	NASA	Ice sheet mass balance, sea level	2018
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 twenty GNSS satellites from four constellations were added to the ILRS priority list. In addition, and as shown in Table 2, four other satellites, including two restricted tracking missions, were launched and supported by the ILRS network. The ILRS tracking roster presently includes six GLONASS satellites, nine Compass satellites, eighteen Galileo satellites, five IRNSS satellites, and one QZSS satellite. Following discussions at the 2012 ILRS Technical Workshop, “Satellite, Lunar and Planetary Laser Ranging: Characterizing the Space Segment,” in Frascati, Italy in November 2012, and agreements that were approved by the ILRS and GGOS after deliberations within the “Laser Ranging to GNSS s/c Experiment (LARGE)” Study Group meeting in April 2014, several stations routinely track segments of passes of all 24 active GLONASS satellites and beyond. The newer “high” satellites are using retroreflector arrays that satisfy the ILRS standard. As a result, stations are having greater ranging success.

Recently, the ILRS has become more involved in supporting Precision Time Transfer by laser ranging. The ILRS network is currently tracking the Jason-2 satellite (launched in 2008) which includes the Time Transfer by Laser Link (T2L2) instrument. The T2L2 instrument records the time of arrival of laser pulses. It provides a means to synchronize the clocks of the 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 is 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 a bias w.r.t. to UTC, sometimes as high as a few microseconds (for example the prolific Yarragadee station had a long-term evolving bias of 1 microsec throughout 2013). While the ILRS requests that stations maintain their timing within 200 ns, the data from T2L2 reveal a source of error that has not previously been considered. Time biases at the level of less than 1 microsec are hard to resolve from the orbit determination analysis, so the data from T2L2 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 “corrected” SLR data to the ILRS analysis centers, based on analysis of data from T2L2.

A precise clock in space provides a worldwide access to high performance ground clocks. Here SLR plays an important role. It provides 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) 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) Network

The LLR results are considered among the most important science return of the Apollo era. Of all the active ILRS observatories there are currently only four which are technically equipped to track retro-reflector arrays located on the surface of the Moon or on spacecraft orbiting around the Moon. In 2016, only two Lunar Laser Ranging (LLR) sites collected ranging data to the Moon: the Observatoire de la Côte d'Azur, France (63 NP's at 532 nm and 756 at 1064 nm (infrared)) and the APOLLO site in New Mexico, USA (273 NPs). Since the latter part of 2014, the Observatoire de la Côte d'Azur LLR station has been able to range with infrared wavelength (1064 nm), these data are available at their website (<http://www.geoazur.fr>) and are included in the statistics shown in Figures 5 to 7. Most of the Observatoire de la Côte d'Azur LLR data are now obtained using infrared instead of green (532 nm) laser pulses.

Unfortunately, no NPs have been obtained from the McDonald Observatory in Texas, USA. This means, a time series of LLR tracking at McDonald, which has run for four decades, has been interrupted. This discontinuation will adversely affect research utilizing LLR data as the McDonald station has been a major contributor to LLR data over a long period of time.

The LLR measurement statistics for 2016 (Figure 5) shows that about 75% of the data have been collected at the French MeO site near Grasse and about 25% of the data at APOLLO. Figure 6 illustrates the statistics for the observed retro-reflector arrays, where much better coverage of all reflectors was achieved than in previous years. Nevertheless, most of the data was obtained on the big Apollo 15 reflector array (48%), while the other four reflectors provided data at the 12-14% level. Figure 7 presents the entire LLR data set from 1970 to 2016 displaying the amount of data collected by each of the active LLR sites in each year. The total data yield over this period is about 22,000 NPs, recently averaging about 600 NPs per year. At the Observatoire de Paris, an “assisting tool” is available to support lunar tracking by providing predictions of future LLR observations as well as a validation of past LLR normal points. This tool and further information can be accessed via the ILRS website at <https://ilrs.gsfc.nasa.gov/science/scienceContributions/lunar.html>.

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.

One general objective of LLR analysis is to improve accuracy from the current cm to the mm level. The various analysis centers continue their comparison initiative to mutually improve the various reduction codes. Recent activities also include comprehensive simulations to show the potential benefit of improved tracking with additional observatories and/or to new reflectors.

Above all, LLR remains one of the best tools to support lunar science, to study the Earth-Moon dynamics and to test General Relativity in the solar system (Müller et al. 2014). LLR analysis steadily reduces the margins for a possible violation of Einstein’s theory of relativity and impressively underpins its validity – now in the 100th year of its existence.

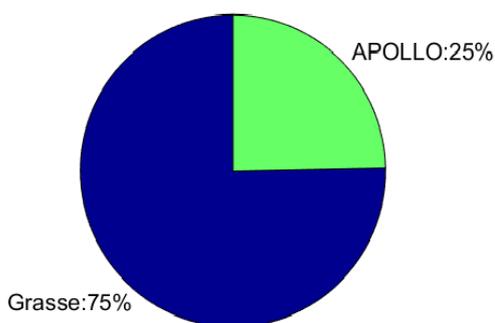


Figure 5. Observatory statistics in 2016.

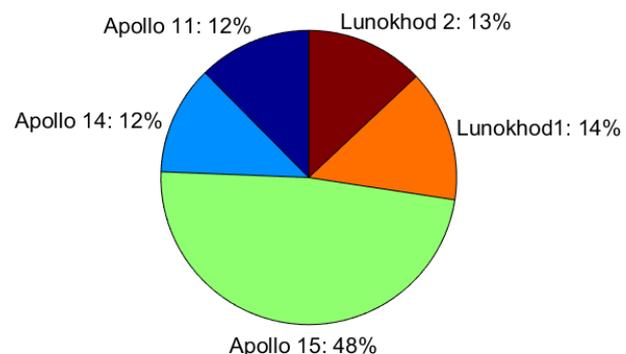


Figure 6. Reflector statistics in 2016.

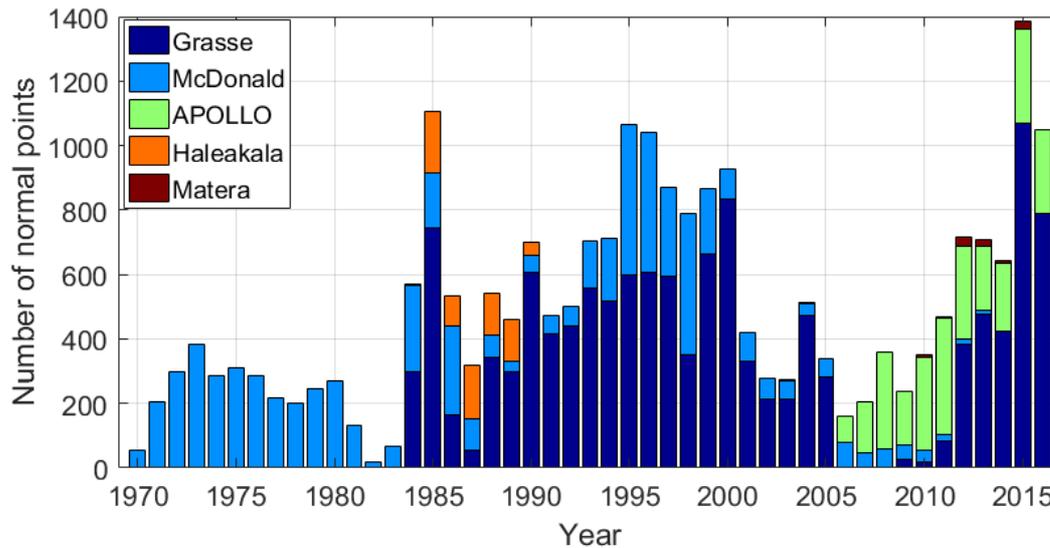


Figure 7. Data yield of the global LLR network of stations (through the end of 2016).

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 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 Progress

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 an 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 as 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 procedure will be implemented as a standard product and the ASC will develop guidelines for identifying likely errors and notify the affected stations. This step is expected to be completed by mid-2017. A subsequent PP will introduce 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 2017. The co-chairs of the ASC are leading 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 and the process is currently in the stage of the review of the abstracts by the guest-editors and the editor in chief to decide which of these will be accepted for publication in the special issue.

Data Formats and Procedures Standing Committee (DFPSC)

Discussions at DFPSC splinter meetings proposed modifications to the ILRS standard CPF and CRD formats that are needed to fine-tune handling of several issues, including transponder missions, day wrap-around, and the need for more lunar and software ancillary data; a study group within the SC will work on these changes. A new procedure was formulated and distributed to ILRS stations for handling the December 31 2016 leap second; this procedure, which mainly directed stations to stop tracking during the leap second, was moderately successful and will be reiterated for future occurrences of leap seconds.

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. Missions approved during the reporting period include: COSMIC-2, LightSail-B, Lomonosov, NISAR, and Sentinel-3A/-3B.

Networks and Engineering Standing Committee (NESC)

The NESC developed a procedure that could be used by ILRS stations to take a series of measurements of their system's beam divergence; measuring laser beam intensities at satellite heights can inform missions of any potential hazard to sensitive on-board equipment. Results of the measurements submitted by participating stations were discussed at the 2016 workshop in Potsdam. The SC continues to review the ILRS Site Log format and consider modifications that would benefit the ILRS and mission operators. The NESC chair established a discussion forum to strengthen the connection, communication, and collaboration between international colleagues and share the experience and knowledge in the ILRS to address problems common to stations in the network. The NESC distributed a questionnaire to the stations about what is needed to address systematics; results from the questionnaire were presented at the NESC meeting in Potsdam.

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 between Wettzell and Graz.

Quality Control Board (QCB)

The ILRS Quality Control Board was organized at the 19th International Workshop on Laser Ranging to address SLR systems 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 monthly basis. Current activities include results from the ASC's "Station Systematic Errors Pilot Project" and development of tools for the stations to view system performance and examine systematic errors. The plan is to have these as web-based diagnostic tools by the latter part of 2017. Several AC's have been routinely examining the incoming SLR data and providing rapid feedback to the stations on suspect performance. The Board is also examining 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 is working its way through the open-sourcing process at NASA GSFC.

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.

Mission Campaigns

LARGE

During the 18th International Workshop on Laser Ranging in Japan in November 2013, the ILRS agreed to expand the ILRS network support for GNSS constellations. The ILRS and GGOS formed a joint study group, the LAser Ranging to GNSS s/c Experiment (LARGE) to define an operational GNSS tracking strategy to improve the ILRS response to GNSS user requirements and to clarify outstanding ILRS and IGS issues with the GNSS satellites and ground stations. The satellite constellations of interest with retroreflector arrays include GLONASS, BeiDou (Compass), Galileo, GPS, IRNSS, and QZSS. The GLONASS constellation is fully populated. BeiDou and Galileo constellations are in process. GPS satellites with laser retroreflector arrays will begin launching in the 2019 timeframe. When completed, the full GNSS complex should reach over 100 satellites.

Several GNSS tracking campaigns have been held since 2014, adjusting priorities to focus on a subset of the GNSS satellites. Some improvement has been seen, but it may also have been the result of stations becoming more familiar with GNSS tracking. Subsequent sessions examined the results in more detail (number of segments per pass, number of normal points per segment, "location" within the pass to acquire the data). More details can be found in a poster presented at the 2015 ILRS Technical Workshop in Matera (Noll et al., 2015). The ILRS is now in a mode of running three-month sessions on selected satellites in each of the GNSS constellations.

GREAT

Monthly campaigns continue 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 induce a periodic modulation of the gravitational redshift at the orbital frequency. Since these spacecraft have atomic clocks with good stability (a passive hydrogen maser clock on Galileo-201 and a rubidium clock on Galileo-202), a test of the variation of the redshift can be performed and an accumulated relativistic effect can be determined over the long term. In response to our Galileo mission request, the ILRS conducted monthly, week-long campaigns for a period of one year in support of the ESA funded experiment, GREAT (Galileo gravitational Redshift Experiment with eccentric sATellites). Stations were asked to observe each pass, sampling data from the beginning to the end, with one or two normal points, maximum of five minutes in duration, about every 50 minutes. The ILRS and the community await results from the 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 3. 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.

The ILRS co-sponsored several workshops over the last three years. 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.

Table 3. Recent ILRS Meetings (as of May 2017)

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

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 looking into issuing these reports in a more streamlined fashion.

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.

Other Activities

In April 2013, the ILRS was accepted as a network member of the International Council for Science (ICSU) World Data System (WDS). The WDS strives to enable open and long-term access to multidisciplinary scientific data, data services, products and information. The WDS works to ensure long-term stewardship of data and data services to a global scientific user community. The ILRS is a network member of the WDS, representing its two data centers and coordinating their activities within the WDS. The WDS requests that all members present a report every two years at its member's forum. In 2016, a poster (Noll and Pearlman, 2016) reviewing the ILRS was presented at the WDS Member's Forum in Denver CO.

Issues and Challenges

Several challenges are on the horizon for the ILRS as it moves forward. Many gaps remain in the ILRS network's geographic coverage, primarily in Latin America, Africa, and Oceania. The ILRS network consists of a mix of new and old technologies and levels of financial support and there is a lack of standardization in system hardware and operations. The number of satellite targets for the ILRS network tracking continues to increase and because of this increase, there is a need to implement more effective tracking strategies. 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; efforts are underway to detect and reduce systematic errors.

References

- Luceri, V., E. C. Pavlis, B. Pace, D. König, M. Kuzmich-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://cddis.nasa.gov/2015_Technical_Workshop/docs/posters/P1.8_Noll_poster.pdf).
- Noll, C., M. Pearlman, (2016) "International Laser Ranging Service: Supporting geodetic and geophysical research and applications through Satellite Laser Ranging", presented at 2016 WDS Members' Forum, Denver, Colorado, September 11, 2016. (https://ilrs.gsfc.nasa.gov/docs/2016/ILRS_WDS_Poster_v4.pdf).
- Pavlis, E. C., V. Luceri, M. Kuzmich-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>).