International Laser Ranging Service (ILRS)

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Chair of the Governing Board: Stephen Merkowitz (USA)
Director of the Central Bureau: Michael Pearlman (USA)

C. Carabajal (USA), F. Lemoine (USA), V. Husson (USA), V. Luceri (Italy), M. Blossfeld (Germany), D. Sarrocco (Italy), C. Courde (France), M. Wilkinson (UK), C. Schwatke (Germany), J. Rodríguez (Spain), U. Schreiber (Germany), J. Kodet (Germany), J. Eckl (Germany), M. Steindorfer (Germany), D. Kucharski (USA)

ILRS website - http://ilrs.gsfc.nasa.gov/

1 Overview

The International Laser Ranging Service (ILRS) is the international organization 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 and transponded time-of-flight measurements to space-borne receivers. These data sets are made available to the community through the Crustal Dynamics Data Information System (CDDIS) and the EUROLAS Data Center (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/LARES/Etalon combination solutions for maintenance and improvement of the ITRF. 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 3 – 5 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 of satellites (LAGEOS and LAGEOS-2, Etalon-1 and -2, LARES and LARES-2) 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.

1.1 ILRS Governing Board (GB) Structure

As of June 2025, the ILRS Governing Board is composed of the following members:

Name	**Position**	**Country**
Ex-Officio Members:		
Michael Pearlman	Director, Central Bureau	U.S.A.
Claudia Carabajal	Secretary, Central Bureau	U.S.A.
Krzysztof Sośnica	Representative of IAG Commission 1	Poland
Daniela Thaller	IERS Representative to ILRS	Germany
Elected Members:		
Sven Bauer	EUROLAS Network Representative	Germany
José Rodríguez	EUROLAS Network Representative	Spain
James Bennett	WPLTN Network Representative	Australia
Zhang Zhongping	WPLTN Network Representative	China
Evan Hoffman	NASA Network Representative	U.S.A.
Stephen Merkowitz	NASA Network Representative, Chair	U.S.A.
Vincenza Luceri	Analysis Center Representative	Italy
Mathis Bloßfeld	Analysis Center Representative	Germany
Justine Woo	Data Center Representative	U.S.A.
Clément Courde	Lunar Laser Ranging Representative	France
Christian Schwatke	ILRS GB At Large Representative	Germany
Matthew Wilkinson	ILRS GB At Large Representative	UK
Appointed Members:		
Takehiro Matsumoto	ILRS GB Appointed Member	Japan
Randall Carman	ILRS GB Appointed Member	Australia

Table 1. ILRS Governing Board Members 2023-2026 as of June 2025.

2 Data Products

The main ILRS analysis products consist of weekly-averaged SLR station coordinates and daily Earth Orientation Parameters (x-pole, y-pole, and excess length-of-day—LOD) on SINEX-formatted files uploaded operatively to the EDC and CDDIS data centers. These parameters are estimated from 7-day arcs of SLR tracking of the two LAGEOS satellites, the two Etalon satellites, and—presumably by the second half of 2025—LARES-2.

The official ILRS Analysis products are delivered daily by sliding the 7-day period covered by the arc forward by one day each day. This approach accommodates two primary users: the ITRS Combination Centers and the IERS EOP Prediction Service at USNO. The former requires a single weekly analysis spanning Sunday to Saturday, while the latter demands timely EOP estimates, which the sliding analysis efficiently provides.

On a weekly basis, orbit products for the Precise Orbital Definition of contributing satellites are delivered in SP3c format (https://doi.org/10.5067/SLR/SLR_ILRSORB_001), referenced to the TRF model active at the time of release together with a weekly product estimating station coordinates and EOP, with a 10-day lag to ensure all tracking data have been submitted to the Data Centers and a stable EOP series is available.

Two types of products are distributed for each 7-day period: a loosely constrained estimation of coordinates and EOP and an EOP-only solution derived from the previous one and constrained to the ITRF, which was ITRF2014 from 01/06/2017 to 31/12/2023 and ITRF2020 from 01/01/2024. A new procedure (SSEM-X) for monitoring systematic errors in the network has been well established through a weekly internal official product: a free solution of SSC and EOP parameters along with a freely adjusted weekly averaged range bias for each of the participating stations (and for each satellite).

The range bias estimates from the combination of the individual ACs' (Analysis Centers) contributions are monitored and coded into a SINEX-like file named Data Handling File (DHF), in which it is reported for each station and for each satellite whether there is the need to estimate or apply a long term mean bias for specific time periods.

Moreover, when a significant and persistent break in the value of a station's mean bias is detected, a break will be introduced in the bias model and a new entry will be initiated. The DHF will be updated accordingly and the affected station will be contacted to investigate and rationalize the observed change. The current bias model can be visualized for each site and satellite target via the JCET Portal (http://geodesy.jcet.umbc.edu/ILRS_AWG_MONITORING) by selecting the option "MODEL BIAS SSEM-X for SLRF2020".

Official ILRS Analysis Centers (ACs) and Combination Centers (CCs) generate individual and combined solutions, respectively, adhering to ILRS Analysis Standing Committee (ASC) standards aligned with IERS Conventions.

As of May 2025, each official ILRS solution combines contributions from eight ACs:

- **ASI**: Agenzia Spaziale Italiana
- **BKG**: Bundesamt für Kartographie und Geodäsie
- **CNES**: Centre national d'études spatiales
- **DGFI/TUM**: Deutsches Geodätisches ForschungsInstitut/Technische Universität München
- **ESA**: European Space Agency
- **GFZ**: GeoForschungsZentrum Potsdam
- **JCET**: Joint Center for Earth Systems Technology and Goddard Space Flight Center
- **NSGF**: NERC Space Geodesy Facility

Following ITRF2020's release, the ASC extended the reference frame to create SLRF2020, incorporating 30 additional SLR sites not present in the ITRF2020. These include historical pre-ILRS stations and newer sites established during or after ITRF2020's development, which lacked sufficient data for inclusion in the original model. After the ILRS contribution to the definition of the new ITRF2020 and the adoption of the new reference frame (DOI: https://doi.org/10.5067/SLR/slr_itrf20200_repro2020_001), the official CCs provided during the last two years, a combined time series solution, for the period 2020-2023, to the IERS for the contribution to the ITRF2020 update: ITRF2020-u2023.

After the inclusion of the LARES-2 data (expected at the second half 2025), a project to evaluate and include satellite LARES data in the official products was planned, as well as other satellites, which will hopefully be included in the next ITRF model.

The products are available from the official ILRS Data Centers:

- CDDIS/NASA Goddard Space Flight Center: https://cddis.nasa.gov/Data_and_Derived_Products/SLR/Reference_frame.html
- EDC/TUM/DGFI: http://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/CC at: http://geodesy.jcet.umbc.edu/ILRS_AWG_MONITORING/.

3 Satellite Laser Ranging

3.1 ILRS Network

The present ILRS network includes forty-five active stations in twenty-two countries (see Fig. 1). Over the years, the network of SLR/LLR stations has been subject to change. The last two and a half years have seen both periods of growth and periods of slower advancement. Presently, we are again seeing more rapid growth. New laser ranging stations being built and brought into operation are expanding the spatial and temporal coverage of the network. By 2025, the network grew with the inclusion of new systems. The Tsukuba, Japan, Izaña, in Tenerife and Yebes, Spain, and Ishioka, Japan stations were added to the network. A new station in China (Xian) has recently joined the network. Other systems are still undergoing upgrades. About 40 % of the stations are meeting a 3500-pass guideline. Many stations continue to have low performance and hence have little contribution to ILRS derived products, which contribute of course to the ITRF. Low data yield in some cases due to station upgrades or technical issues, other times due to weather, and we hope to see greater yield in future. From a technical perspective though, the quality and quantity of the observations has remained relatively similar during the past few years. The single-shot precision of an average station during 2023 is better than 10 mm (for the best stations this number is a few millimeters. The absolute quality of the individual observations is on average at the 10 mm level, with the best one dozen stations doing significantly better. Nearly all stations deliver normal points (NPs) with a precision of 1 mm or better, a firm requirement for the GGOS-era network as outlined in the GGOS2020 document, and several stations have upgraded to high repetition rate systems to meet such requirements.

All of the progress achieved by Russia and Ukraine since 2015 has significantly slowed down since the conflict started in early 2022. The pandemic delayed several system upgrades. Other system updated were affected by budget constraints, and in some cases import restrictions. There are still plans to upgrade the system at Metsahövi (Finland), the upgrade of the Chinese SLR station in San Juan (Argentina) is still underway, and the SLR system in the Argentine-German Core Geodetic Observatory (AGGO) now in La Plata, Argentina, is also undergoing upgrades. The two new stations planned at Ponmundi and Mt. Abu (India), have suffered substantial delays and have uncertain plans.

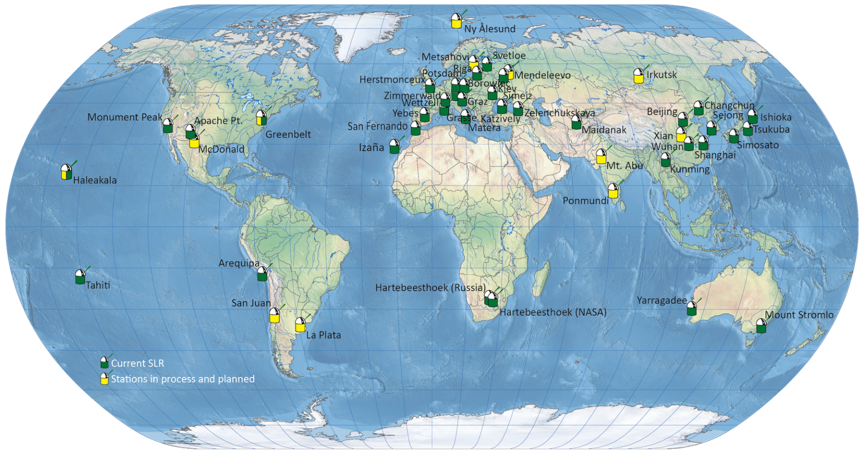

Fig. 1. Current and Planned ILRS network as of June 2025.

Large progress has been made by the NASA Space Geodesy Project (SGP), building new SLR systems as part of a new Core sites at Ny-Ålesund (Norway) in coordination with the Norwegian Mapping Agency, and with the replacement for legacy SLR systems at Core sites at GSFC (MD), McDonald TX, and Maui (HI). Deployment is now projected for the 2026 – 2028 timeframe.

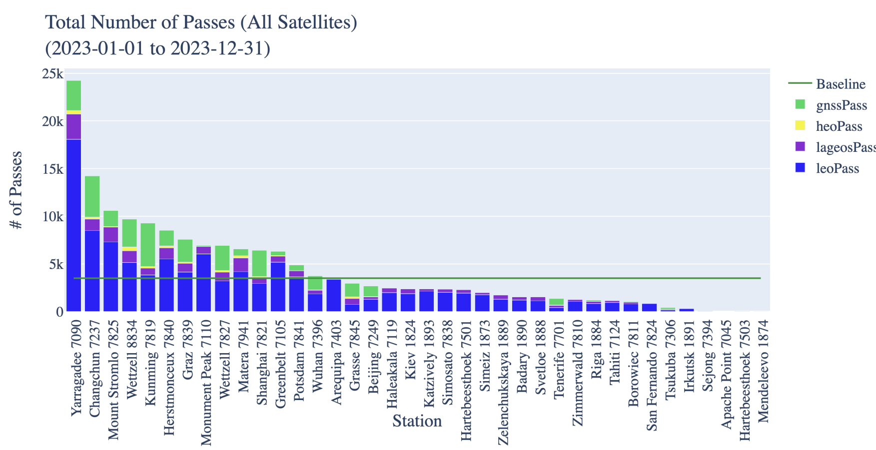

Fig. 2. ILRS Network Performance (Total Number of Passes, all Satellites) from January 1st, 2023, December 31st, 2023.

Planning is also underway for additional SLR systems as part of Core sites at other current NASA partner locations and new locations. Large gaps are still prominent in Africa, Latin America, and Oceania, while new partnerships are being explored.

The network performance during 2023 (see Fig. 2) and 2024 (see Fig. 3) shows that some stations continued to operate well. Strong performers are shown on the left side of the plots.

Stations designated as operational have met the minimum ILRS qualification for data quality and quantity. During those years, fifteen stations met the ILRS minimum requirement for total numbers of passes tracked:

- 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)

Interleaving tracking on several satellites at the time in many stations is enabled by stations operating at high repetition rates. Many stations have implemented automated procedures to expand operating hours. Some stations have demonstrated mm precision normal points, making it possible to achieve the reference frame requirements.

3.2 Lunar Laser Ranging Network

There are currently four active ILRS observatories, which observe the lunar retroreflectors and distribute theirs observations on CDDIS/EDC. These stations are Apache Point (USA), Grasse (France), Matera (Italy) and Wettzell (Germany). For several years, Grasse and Wettzell range in infrared (1064 nm), while Matera and Apache Point range in green (532 nm). New stations are operating in China (Kunming station and the TianQin station) with new technology (SNSPD detection for the TianQin station) but they do not share their data to the ILRS network for the moment. Stations are also under development in China (ChangChun, and Shanghai), in Russia (Altay Optical-Laser) and in South Africa (the Hartebeesthoek Radio Astronomy Observatory where an ex-Observatoire de la Côte d' Azur 1-m aperture telescope is being prepared for LLR use). New technical solutions are also envisaged like extending observations at high repetition rate in SLR to LLR or trying to obtain differential measurements.

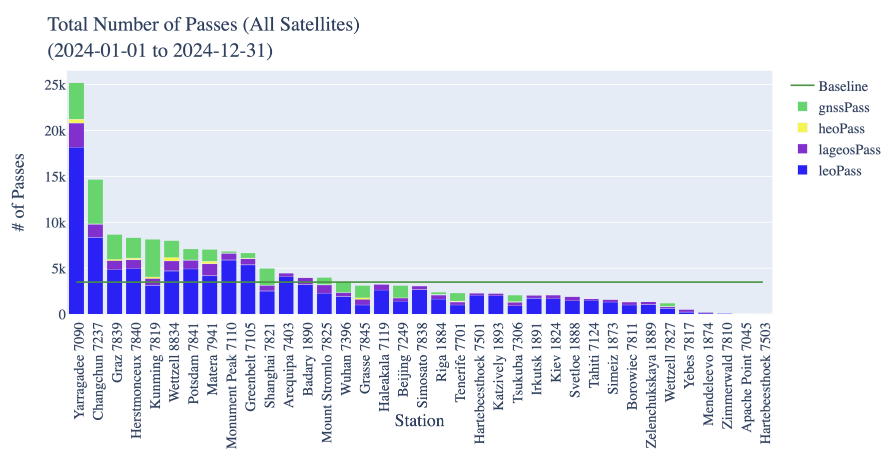

Fig. 3. ILRS Network Performance (Total Number of Passes, all Satellites) from January 1st, 2024, December 31st, 2024.

3.3 Lunar Analysis Centers

The six Lunar Laser Ranging (LLR) analysis centers focus on different research topics (Fig. 4). The centers perform Lunar ephemerides updates, LLR data validation, proving other products like Lunar retroreflector coordinates, Lunar Principal Axis (PA) reference frame definition, Lunar Geophysical Parameters, and tests of general relativity (GR). Some interest towards this end has also been shown by the Hartebeesthoek Radio Astronomy Observatory (South Africa). In addition, various research projects have been successfully run combining LLR, GRAIL, and LRO data. Lunar dynamical models and analysis tools have the potential to improve and fully exploit the long temporal baseline and precision allowed by millimetric LLR data. LLR model improvements would impact multidisciplinary fields that include lunar and planetary science, Earth science, fundamental physics, celestial mechanics and ephemerides.

ILRS Lunar Analysis Centers	Contact
Goddard Lunar Data Analysis Center (GLD AC), Greenbelt, MD, USA	Dr. Vishnu Viswanathan
Forschungseinrichting SatellitenGeodasie/Institut fuer Erdmessung (FESG/IFE), Germany	Dr. Ing. Jurgen Mueller
Instituto Naz. di Fisica Nucleare - Laboratori Naz. di Frascati (INFN-LNF), Italy	Dr. Simone Dell'Agnello Marco Muccino Luca Porcelli
Jet Propulsion Laboratory, Pasadena, California, USA	Mr. James Williams
Paris Observatory Lunar Analysis Center, France	Dr. Sebastien Bouquillon
Russian Academy of Sciences/Institute of Applied Astronomy (RAS/IAA)	Dr. Alexander Ipatov

Fig. 4. ILRS Lunar Analysis Centers

4 Lunar Laser Ranging Science

The Lunar Laser Ranging (LLR) experiment has accumulated 50 years of range data of improving accuracy from ground stations to the laser retroreflector arrays (LRAs) on the lunar surface. From 2023 to 2025, various scientific results obtained from LLR have been published:

- The combination of data from various space missions and laser ranging data from the Moon has revealed a solid core approximately 500 km in diameter, or about 15% of the Moon's size. It is composed of a metal with a density close to that of iron [1].
- New test of the possible violation of the equivalence of passive and active gravitational masses *(ma/mp)* for aluminium (Al) and iron (Fe) has been done using LLR data. A new limit of 3.9×10-14 is approximately 100 times better than the last test of this type carried out in 1986 [2].
- The first laser retroreflector on the Lunar far side onboard China's Chang'E-6 lander had softly landed in the Apollo basin within the South Pole-Aitken basin. The LRO's LOLA altimeter has successfully tracked the Instrument for landing-Roving Laser Retroreflector Investigations (INRRI) deployed on the lander top panel. Future observations by laser ranging from lunar orbiters will refine its positional data, and may contribute to advancing our understanding of Earth-Moon dynamics and lunar physics [3].

- The successful moon landing of the Blue Ghost mission (NASA-CLPS Firefly Aerospace) with the new NASA-Next Generational Lunar Retroreflector (NGLR-1) reflector on the morning of Sunday March 2, 2025, in Mare Crisium, a large lunar basin at 17.0°N, 59.1°E in the northeast quadrant of the lunar nearside on March 2, 2025 at 08:34 UTC.

NGLR-1 was procured by the University of Maryland (College, Park, Maryland, USA), with D. Currie (UMD) as Principal Investigator. A pre-flight NGLR prototype was contributed by the INFN (Istituto Nazionale di Fisica Nucleare) - Frascati National Labs, Italy, long-time partner of this UMD development [4]. The Blue Ghost Lander was delivered to the lunar surface under the auspices of the NASA CLPS (Commercial Lunar Payload Services) initiative (see Fig. 5).

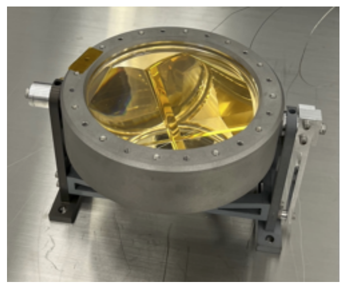

Fig. 5. The Next Generation Lunar Retroreflector (NGLR). Credit: D. Currie (University of Maryland, College Park, MD, USA).

The NGLR-1 reflects very short laser pulses from these Earth-based Lunar Laser Ranging (LLR) Observatories. The laser pulse transit time to the Moon and back will be used to accurately determine the distance between the terrestrial station and NGLR on the surface of the Moon. NGLR will improve upon the Apollo and Luna LLR results by providing sub-millimeter range measurements due to its unique location and smaller target signature.

Three LLR stations of the ILRS confirmed that they successfully ranged to NGLR-1: Grasse, France (at both the green and infrared wavelengths); Wettzell, Germany (at the infrared wavelength); and the Apache Point Observatory in New Mexico, U.S.A (at the green wavelength). See [5]; [6]; [7] for descriptions of the Apache Point, Wettzell and Grasse LLR systems and their data.

The initial position of NGLR-1 resulted in timing offsets during ranging on the order of 600 ns. After refined lander positions were provided by the Blue Ghost Lander/Firefly team, and by the Lunar Reconnaissance Orbiter Camera (LROC) on NASA's Lunar Reconnaissance Orbiter (LRO), the timing offsets were reduced to about 60 ns. The ILRS Paris Observatory Lunar Analysis Center (POLAC) provided the NGLR-1 pointing predictions that were used by the LLR observatories (see Fig. 6). The ILRS stations will continue to range to NGLR-1 along with the other retroreflectors on the lunar surface, enriching the more-than-50 year data set of LLR observations [c.f. see [8]]. Initially the goal will be to characterize the performance of NGLR-1 compared to the experience with the Apollo and Luna retroreflectors. NGLR-1 will also become a ranging target for NASA's Lunar Orbiter Laser Altimeter (LOLA), as LOLA continues to observe different lunar laser reflectors on the surface from lunar orbit. The success of NGLR-1 opens up new scientific perspectives in Fundamental Physics and Seleno-Physics. The new reflector's choice of architecture, a single corner cube, is one of the

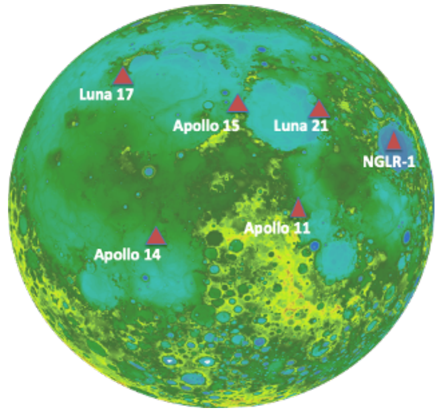

Fig. 6. Location of Lunar Laser Retroreflector Arrays on the Moon overlain on a map of lunar topography provided by NASA's Lunar Orbiter Laser Altimeter (LOLA). Credit: NASA and the Lunar Reconnaissance Orbiter (LRO)/LOLA.

key for more precise measurements and for new studies in gravitational physics, Earth and Moon geophysics, geodesy, and dynamics.

5 Satellite Missions and Campaigns

More than 150 targets are being tracked by the ILRS Network (Fig. 7 and Fig. 8). Only about 1/3 are geodetic targets (cannonball satellites), about one half are navigation satellites (GNSS) and the rest are Earth Observation missions, including a small number of experimental space science missions. In addition to LARES, added to the LAGEOS class satellites in 2012, LARES-2 launched on July 13th, 2022. Tracking by the ILRS network began on July 13th, 2022.

The ILRS CB and members of the various Standing Committees have been actively participating in ESA's Genesis mission, providing inputs into the mission requirements through simulations and analysis. The SLR working group has participated in several meeting and most recently in the Genesis Science Workshop 2025, organized by ESA. Clément Courde was chosen by ESA as the Chair of the SLR working group. The Working Group tasks involve:

1. Providing support to ESA to assess the SLR reflector compatibility with ground Stations.
2. GENESIS SLR data: Define formats for data delivery and data products.
3. SLR observation campaign organization: Station recommendations and observation strategy.
4. Support the definition of the SLR payload calibration approach (on the ground and on-orbit).
5. Interface with the ILRS.

5.1 Mission Campaigns

The Indian Space Research Organization (ISRO) requested a first tracking campaign for IRNSS- 1J (NVS-01) from December 20th, 2023 until January 10th, 2024, with other follow-

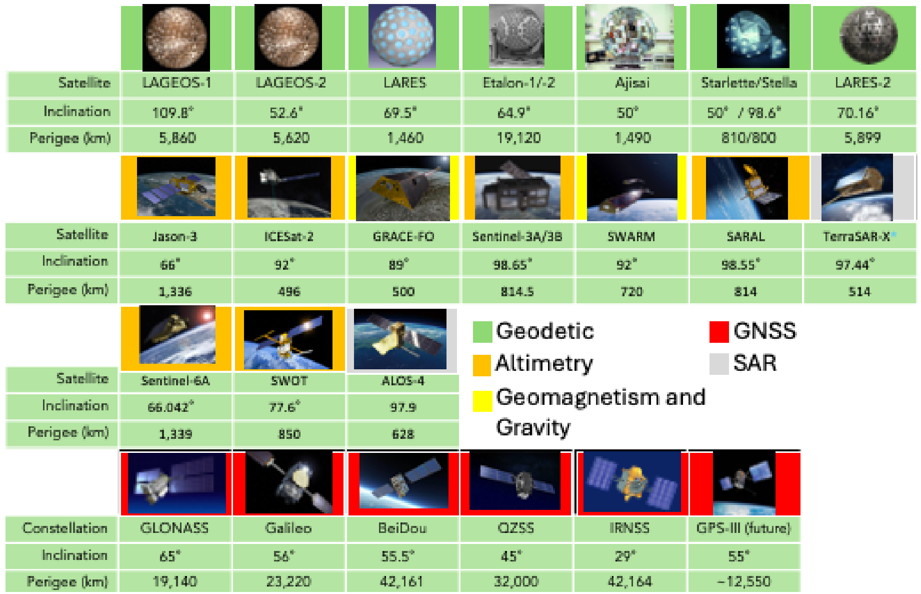

Fig. 7. Type of missions currently supported by the ILRS.

on campaign sessions planned for later. The plan was to carry out experiments on satellite-based navigation techniques using NVS satellites and estimation of NVS satellite orbits and clock on a real time basis. In these experiments, ISRO has planned to study the techniques of "Onboard atomic clock performance evaluation", clock synchronization technique between satellite and ground, ranging error estimation techniques and precise orbit determination techniques for Geostationary and Geo-Synchronous satellites. Laser ranging will help the mission to determine the orbit of NVS satellites precisely and for the evaluation of the orbit determination accuracy. SLR measurements will also be used to evaluate time synchronization between ground clock and onboard clocks and to establish the SLR tracking techniques for Geo-Stationary and Geo-Synchronous satellites. The SLR tracking data will be used to supplement and calibrate the ISRO Code-division multiple access (CDMA) ranging systems.

The ILRS supported tracking of the Advanced Land Observing Satellite-4 (ALOS-4) satellite for a one-month campaign that started on November 25th, 2024. A tracking campaign for QZS-6, part of the Quasi-Zenith Satellite System (QZSS), is currently underway. It started on April 25th and will continue through June 27th, 2025. Restricted tracking of QPS-SAR is to start in August of 2025 by those participating stations that have fulfilled the mission requirements and signed agreements with the ILRS.

5.2 Galileo for Science Campaign

The ILRS approved the network's participation in the Galileo for Science project in 2023. Funded by the Italian Space Agency (ASI), the project aimed to perform a set of measurements in the field of gravitation with the Galileo satellites of the Full Operational Capability (FOC) constellation. The project wanted to take advantage of the accuracy of the on-board atomic clocks and, in particular, of GSAT0201 and GSAT0202 by exploiting their relatively high eccentricity (approximately 0.16). The Research Institutes Involved in this project in-

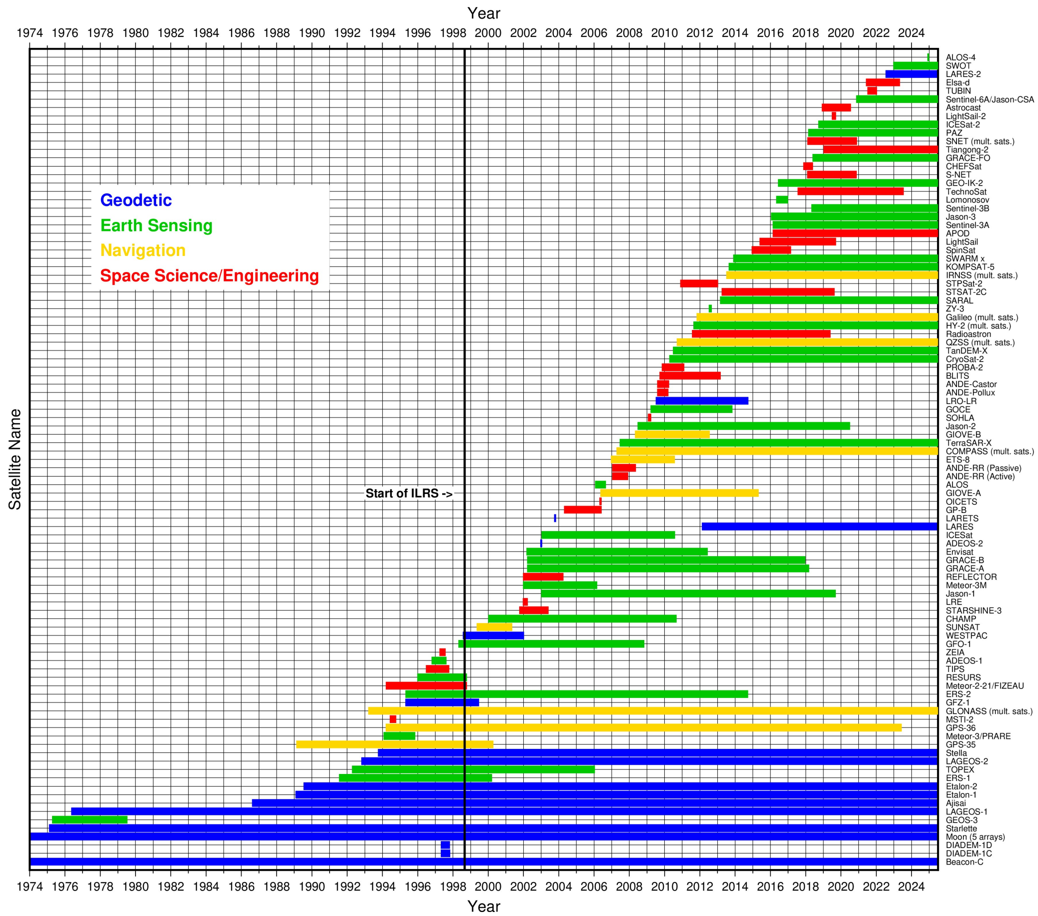

Fig. 8. The past and current ILRS satellite tracking list as of June 2025.

clude ASI-CGS (Center for Space Geodesy) in Matera, Italy, the Instituto di Astrofisica e Planetologia Spaziali (IAPS/INAF) in Roma, Italy, and the Osservatorio Astronomico di Torino (OATO/INAF) in Torino Politecnico (POLITO) in Torino, Italy. The main goals of the project are:

- A new measurement of gravitational red shift
- A measurement of relativistic precessions on the two satellites in eccentric orbit
- Constraints on Dark Matter in the Milky Way
- Relativistic Positioning System
- Development of new models for non-gravitational forces
- Development of a new accelerometer concept for a next generation of Galileo satellites

There are approximately 22 satellites in the Campaign. The project requested that the ILRS Network average at least 10 Normal Points (NPs) per satellite per day. ILRS suggested that stations try to take 3 - 5 NP's on as many of the Galileo satellites as they can each day, trying other satellites the next day. The Galileo for Science project will be analyzing all the data collected from the beginning of the campaign. The first phase started on January 20th through April 30th, 2024. The next phase of the campaign started on May 1st, 2024.

Galileo for Science Campaign Pass Totals (Current Week)																
Pad	Location	101	102	103	201	202	203	205	206	208	209	210	211	212	221	**Total**
1873	Simeiz															
1884	Riga							1								**1**
7090	Yarragadee	2	2	1	3	2	1		1	1	1		2			**16**
7105	Greenbelt												1			**1**
7110	Monument Peak															
7124	Tahiti															
7237	Changchun							1			1			1		**3**
7249	Beijing									1			1	1		**3**
7306	Tsukuba															
7396	Wuhan							1	1	2	1					**5**
7501	Hartebeesthoek															
7701	Izana	2											1			**3**
7810	Zimmerwald	1	1	1	1					1	1	1			1	**8**
7811	Borowiec															
7817	Yebes															
7819	Kunming							1	1	1	1		1	1	1	**7**
7821	Shanghai	1	1	1				1		1	1					**6**
7825	Mt Stromlo		3		5	1	1	1		2	4		1	1		**19**
7827	Wettzell					1		1	2				1	1		**6**
7838	Simosato															
7839	Graz	2	1	1	1	1		1	3	1	2		2	1	1	**17**
7840	Herstmonceux								1	1	1	1	1	1	1	**7**
7841	Potsdam									1	1		1	1		**4**
7845	Grasse	2	1	1	2	1		1	2		3	2	1		1	**17**
7941	Matera		2		2	3					1	3	3			**14**
8834	Wettzell			1	2	1	1	1		2	1		2	1	2	**14**
	Totals	10	11	6	16	10	3	10	11	14	19	7	18	9	7	**151**

Fig. 9. Galileo for Science Campaign Pass Totals for the week ending June 4th, 2025. Galileo satellites with elliptical orbits are highlighted in yellow.

Tracking now is focused on the two Galileo satellites with elliptical orbits, Galileo 201 and 202. The other satellites' tracking follows the posted priorities. The ILRS anticipates that other changes will made later on during the campaign. Participation by the network is very important to the Galileo campaign and to those still using the full Galileo constellation. The ILRS has urged the network to do what they can to participate and help make this campaign a success. Each week, the ILRS posts the statistics for the previous week and the aggregate statistics for the campaign since it started (https://ilrs.gsfc.nasa.gov/science/SLR_science_campaigns/galileo_for_science.html) (see Fig. 9 and Fig. 10). The Project has also furnished SLR Campaign Website to monitor how the network is doing, and which satellites need tracking help (See https://g4s-duepuntozero.iaps.inaf.it/campaigns).

Galileo for Science Campaign Pass Totals (Aggregate)																
Pad	Location	101	102	103	201	202	203	205	206	208	209	210	211	212	221	**Total**
1873	Simeiz						1	1				1				**3**
1884	Riga		17	23	16	12	9	19	15	13	16	19	21	12	13	**205**
7090	Yarragadee	203	205	190	201	188	87	118	133	114	129	143	163	109	127	**2110**
7105	Greenbelt	11	53	14	24	28	29	21	18	39	50	32	35	37	40	**431**
7110	Monument Peak	10	23	13	8	21	19	16	19	19	15	17	7	16	14	**217**
7124	Tahiti		2		3		2			2		1		2		**12**
7237	Changchun	114	110	117	84	90	123	79	89	111	111	88	82	108	114	**1420**
7249	Beijing	46	54	34	40	36	51	29	34	33	25	23	27	39	46	**517**
7306	Tsukuba	43	42	45	35	38	39	30	26	33	38	25	28	36	35	**493**
7396	Wuhan	24	28	33	26	28	30	30	37	30	15	28	32	29	35	**405**
7501	Hartebeesthoek		1													**1**
7701	Izana	26	26	29	24	28	18	21	23	31	24	20	23	29	23	**345**
7810	Zimmerwald	7	4	7	2	1	1	3	4	4	4	5		3	2	**47**
7811	Borowiec	1		4	5	1	1		1	6	2	1				**22**
7817	Yebes	6		4	4	2	4	2	2	4	3	1	1	3	6	**42**
7819	Kunming	92	101	111	75	88	101	79	84	109	108	73	74	101	106	**1302**
7821	Shanghai	67	63	61	37	44	42	48	50	54	46	41	53	50	52	**708**
7825	Mt Stromlo		105		97	102	59	44	46	34	97	45	58	24	13	**724**
7827	Wettzell	20	18	19	18	18	14	17	18	16	23	12	18	23	18	**252**
7838	Simosato		1								1					**2**
7839	Graz	88	82	76	89	86	88	64	86	88	75	84	85	69	86	**1146**
7840	Herstmonceux	70	106	75	82	114	64	73	75	83	115	81	69	77	70	**1154**
7841	Potsdam	49	38	59	39	31	35	39	54	33	41	38	38	41	44	**579**
7845	Grasse	72	67	71	96	86	53	67	81	61	72	84	60	49	53	**972**
7941	Matera	38	118	40	172	161	33	32	39	41	92	112	105	34	44	**1061**
8834	Wettzell	13	150	109	110	128	101	80	92	76	122	91	109	83	91	**1355**
	Totals	1101	1516	1237	1488	1533	1207	1117	1232	1242	1433	1275	1299	1186	1253	**15525**

Fig. 10. Galileo for Science Campaign aggregated Pass Totals since the beginning of the campaign up to June 4th, 2025. Galileo satellites with elliptical orbits are highlighted in yellow.

6 Lunar and Planetary Ranging and Time Transfer

6.1 The Atomic Clock Ensemble in Space (ACES)

The European Laser Timing (ELT) is a follow up experiment on T2L2. The ACES payload is located at the Columbus module of the International Space Station (ISS). It was launched on April, 21, 2025 on a Falcon 9 rocket under the mission identifier CRS SpX-32. Fig. 11 is an artist's rendering of the deployment at the Columbus module of the ISS.

Fig. 11. An artist's rendering of the ACES payload at the Columbus module of the ISS. At the lower left side of the payload container, one can see the retro reflector with the 1-way ELT detector for the time transfer.

The ACES payload [9] contains two different clocks, an active hydrogen maser (SHM) and the cold atom cesium clock (PHARAOH). Furthermore, the payload features two independent clock comparison techniques, namely the microwave link (MWL) and the optical time transfer link. There is a GNSS receiver onboard, that can track the path of the clocks in space and there is the cube corner reflector (CCR) in close proximity to the optical time transfer detector unit. To comply with the limited electrical power and weight resources, ELT was designed to minimize the complexity in space and shift it towards the ground station. Apart from the clocks, the ELT package differs from T2L2 by utilizing only a single photon avalanche diode. The APD is gated from the ISS time scale every 10 ms, That means that the ground station has to actively control the laser fire instant, such that the laser pulse arrives at the detector within the first 100 ns after gate on. This is a very dynamic requirement. Furthermore, there is no adjustment for the threshold setting of the detector available and there is no correction for the detector time walk either. The laser pulses must be adjusted by the ground station to the point that single photon detection is ensured during the measurements. ELT is using the timer functionality of the MWL. It does not require an event timer of its own. Instead of the 9.5 kg payload weight and 45 watts of power consumption of the T2L2 experiment, ELT features less than 1.5 kg in weight (including the CCR array) and much less than 1 watt of power consumption.

In order to detect the SLR pulses over a wide angular range, the ACES detector features a detection range of 120°. Since the detector has the most amount of background light coming from the nadir direction, there is a beam block, which blocks the light from the nadir direction.

SLR is a two-way measurement technique, therefore much of the clock drift cancels out in the measurement process. The advantage is the long-term stability of this measurement concept. We have performed an evaluation experiment [10] in order to study the stability that the optical time transfer would add to the ACES project. T2L2 performed very well, but was limited by the stability of the USO clock. ACES should be suitable both for common view and non common view time transfer, the latter suggests test of fundamental physics, by studying a fast moving clock in a low earth orbit. Common view time transfer to the ELT package with two or more SLR stations automatically would provide the possibility to compare high quality optical clocks on ground via the ELT time transfer link, which is known in the literature as chronometric leveling.

Chronometric leveling with the ACES package

The tick-rate of a clock, actually any clock, depends on the physical properties of the location of operation. Whether it is a clock exploiting well defined energy state of atoms or a hourglass, when they are compared at different gravitational potentials or under different velocities, they behave in the same way. While chronometric leveling by frequency comparison is already an established technique for optical clocks that are connected via a delay compensated fiber link, this technology cannot bridge oceans, therefore optical time transfer by a free space satellite link provides a viable alternative, which we explore here, because SLR is the physical realization of the Einstein synchronization process, which is the only solution for the accurate comparison of remote time scales.From general relativity we expect that the clock further away from the center of gravity, will run faster than the other clock, closer to the center of gravity. The clocks will differ in the tick-rate by a correction value proportional to $(1+g\ h/c^2)$. A change of the tick-rate of 1 part in 1018 of a clock on the earth surface corresponds to lifting it up by approximately 1 cm. Only top end optical clocks are good enough to be used for this purpose. In order to exploit this effect experimentally we are performing the experiment sketched in Fig. 12. The main goal is the comparison of several remote strontium lattice clocks, one of them located at the Geodetic Observatory Wettzell and the others operating at the national metrology institutions (NMI) in Braunschweig and Paris. We note, that this project performs time transfer, rather than a frequency transfer, as per the terrestrial links. This is a requirement that follows from the Einstein Synchronization. Otherwise we would loose the information about the distance between ground station and satellite clock and this information is needed for the clock comparison. Therefore, we have to integrate the tick-rate of the clocks continuously and repeat the measurements frequently over a number of overhead passes of the ISS.

With the gravitational acceleration $g = 9.81\ m/s^2$ and the expected height difference of 530 m for the Wettzell - Braunschweig link, we get for the fractional frequency difference $\Delta f = 5.785 \times 10^{-14}$. Multiplied with the transition of a strontium lattice clock (429 THz) this gives a difference in the clock transition of 24.8 Hz, which gives a tick-rate difference of 5 ns in a day. Integrating over several days will allow to establish the actual height difference with good resolution and an uncertainty of less than 20 cm is expected. To achieve that, all clocks in this comparison must run continuously. The operation of these 3 links is the primary goal of this feasibility study, because the clocks in Braunschweig and Paris can also be compared over a compensated fiber link. This means that there is an unprecedented opportunity for a cross characterization uniquely available. The participation of more stations on other continental plates are in preparation (USA, South-Korea). We also encourage other

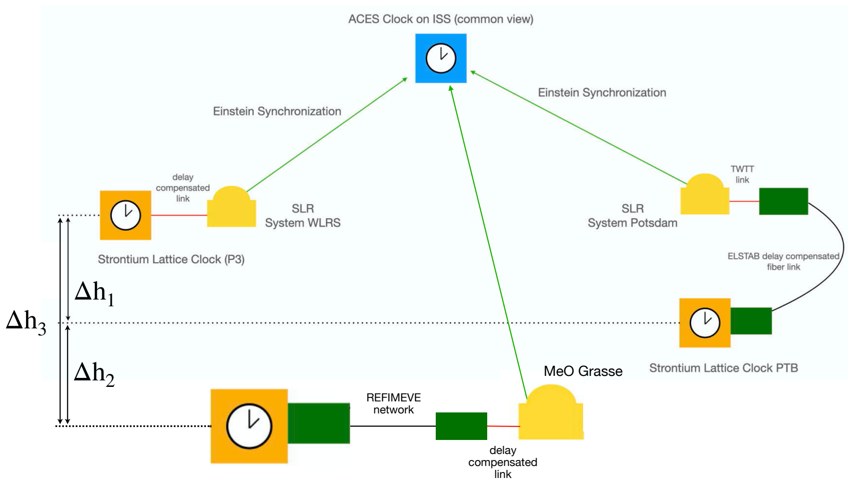

Fig. 12. Schematic concept of the chronometric leveling experiment with ELT.

SLR stations to contribute in order to develop this technology further and to study the details of the gravitational redshift of a stable clock in space.

It remains to be seen over the next 2 years, how well the height difference can be established with current technology. In a ground based local experiment at the top and the bottom of the Tokyo tower a remaining error for the chronometric leveling of Δh $= \pm3.9$ cm has been demonstrated [11]. This compares to a remaining leveling error by GNSS evaluation and laser ranging, carried out on the same platform of Δh $= \pm1.3$ cm.

6.2 Other experiments

In addition to the ESA-ACES experiment, a laser time transfer experiment has been conducted on the Chinese Space Station (CSS). High-precision Time-Frequency Rack (HTFR) mission, a part of the experiment module II on the CSS, was equipped with a Sr optical clock, H-maser, and laser-cooled microwave clock. To compare time and frequency across widely separated clocks, a microwave link, and a pulsed laser link were both established ([12]; [13]).

7 Recent activities 2023-2025

The ILRS Central Bureau (CB) meets monthly to review network station operations and performance, to coordinate support for upcoming missions, monitor and manage the ILRS infrastructure, and plan future activities and direction. The ILRS continues to maintain the ILRS website https://ilrs.gsfc.nasa.gov/. The Standing Committees and Study Groups typically meet during workshops and other scientific meetings. The ILRS Quality Control Board (QCB) continues to investigate SLR system biases and other data corruption issues that can degrade the ILRS data and derived products. Including members of the Analysis Standing Committee (ASC) and the Networks and Engineering Standing Committee (NESC), meets regularly on a bimonthly basis. The QCB continues to address issues with station survey errors, deteriorating calibration stability, and issues with retroreflector array modeling.

7.1 Analysis Standing Committee (ASC)

In the reporting period, all operational products of the ASC have been produced and delivered. The main efforts of the ASC, however, focused on the permanent continuation of the ASC SSEM (Station Systematic Error Monitoring, internally called SSEM-X) project. The main result of SSEM-X is the ILRS data handling file (DHF) which allows the user to account for systematic errors that describe primarily the long-term performance of the ILRS stations. The ILRS DHF provides long-term mean range biases for the geodetic spheres LAGEOS-1/-2 and Etalon-1/-2 for all ILRS network stations since 1976 which must be applied when SLR observations to the above-mentioned four satellites are analyzed, and no range biases are estimated. Moreover, information on time and pressure biases as well as on periods in which data should not be used is provided in the DHF. The DHF is frequently updated, and the bias entries are revisited, new stations are included, and errors are corrected.

Another focus of the ASC was the in-time contribution to the two ITRF2020 updates during the reporting period. The ASC provided reprocessed combined solutions to the ITRF2020-u2023 and ITRF2020-u2024 updates. The reprocessing was based on the weekly operational TRF+EOP solution with only small modifications such as an updated target signature model and an updated DHF. For the ITRF2020-u2023, the period between 2021 and 2023 was reprocessed, for the most recent update (ITRF2020-u2024), the year 2024 was reprocessed. Consistently to the ITRF2020-u2023 update, a reprocessing of the satellite orbits of the above-mentioned four satellites was performed and combined orbits consistent to the ITRF2020-u2023 update have been provided to CDDIS and EDC.

In the reporting period, the ASC also worked on the inclusion of the LARES-2 satellite into the operational products of the ASC. Therefore, the DHF was modified to also include LARES-2 range biases for all currently operated ILRS stations. The target signatures already have been provided by José Rodriguez. Currently, the ASC is monitoring the performance of an operationally computed five-satellite solution in comparison to the official four-satellite solution comprising LAGEOS-1/-2 and Etalon-1/2 observations.

In 2024, a new Analysis Center (AC) hosted at CNES (France) officially joined the ASC and now contributes operationally to all official ASC products. In the last months of the reporting period, the ASC worked on updates of the SLR-specific version of the ITRF2020, the SLRF2020 (new stations and refined coordinate estimates were incorporated). The ILRS eccentricity file was updated accordingly. Smaller topics of the ASC in the reporting period have been the formulation of recommendations to the IERS for SINEX format updates, a survey on satellite-/station-weighting strategies applied within the ASC. Frank Lemoine and his colleagues revisited the station quarantine release process and formulated together with the ASC chairs new thresholds for stations to meet to get released from quarantine.

Finally, the ASC is working on the next pilot project (PP) called "LARES and spherical harmonic estimation". In this PP, the ASC is paving the way to include the Low-Earth-Orbiting (LEO) satellite LARES into its operational products as well as to enlarge the official product portfolio by an operational gravity field product based on a combination of normal equations comprising low-degree gravity field coefficients. Other ongoing efforts of the ILRS ASC are the publication of three planned papers on the ILRS contribution to the ITRF2020 (and its updates), the impact of LARES-2 on the operational TRF+EOP products of the ASC and on the ASC and its operational products itself.

7.2 Missions Standing Committee (MSC)

The Missions Standing Committee (MSC) reviewed mission support requests from the following missions:

- HTV-X (JAXA)
- NVS-01 (ISRO)
- ADRAS-J (Astroscale)
- MSS-1A (Gov. Macau Special Administrative Region of the PRC)
- Nano-FF1/2 (TU Berlin)
- e-kagaku1 (e-kagaku Association of Global Science and Education)
- ALOS-4 (JAXA)
- NGLR (University of Maryland)
- QPS-SAR (iQPS Inc)
- QZS-6 (Cabinet Office, Japan)
- EpsilonS (JAXA)
- Sentinel-6B (ESA)

All applications in the period were ultimately recommended for tracking support, after considerable discussion and clarification with the mission in several cases. Not all missions have been launched, some did not end up making use of ILRS tracking as a resource (i.e ADRAS-J). Missions are ecouraged to engage with the ILRS and the MSC as early as possible to coordinate ILRS support. Early in the 2023–2025 period, we undertook a renewal process to refresh the membership of the standing committee. Members were encouraged to confirm their commitment to fully participate or remove themselves from the group. The MSC recruited several new members to keep the breadth of expertise available as wide as possible.

The MSC Co-Chairs have been active participants in the ESA Genesis Working Group 5, focussed on SLR matters. In particular, they contributed to discussions regarding the proposed retroreflector array design and its optical cross section, essential questions to be answered for the future success of the mission regarding laser tracking. The ESA Genesis mission is of critical importance for the future combination of space geodetic techniques, and the MSC is committed to ensuring all steps are taken to enable both, the most efficient data collection possible and the most effective utilization of the data.

7.3 Networks and Engineering Standing Committee (NESC)

NESC draws on the experience, knowledge, and creativity of the global ILRS network in order to advance the SLR technique and boost the performance of every station. It aims to strengthen links and promote collaboration, information sharing and best practice. It also provides a practical source of advice to other areas of the ILRS.

NESC meets online every two months. Approximately 40 people attend each time and the agenda is made up of contributions from colleagues and invited speakers. Recent meetings have included:

- Station reports from Zimmerwald in Switzerland, Onmi-SLR in Japan, San Fernando in Spain and Potsdam in Germany.
- An overview of SLR tracking to the Beidou-3 satellites since the ILRS adopted the policy of tracking the whole constellation.
- Systematic biases at stations as observed by Earth observation satellites, such as the Sentinel 6, 3A+B, Jason-2+3, CryoSat-2, Saral/AltiKa, Swarm-A/B/C and GRACE Follow-On 1+2.
- Presentations from outside companies to promote new technology.
- Site surveys at the McDonald Observatory, USA and in Grasse, France.
- An update on the search for dark matter using the clocks onboard the Galileo satellites, following an intensive SLR tracking campaign in 2021.
- Detecting aircraft for in-sky safety using an infra-red camera.

- A proposal for a laser range correction test facility.

A Station Survey and Plan document was drafted by the NESC that was intended for those stations not reaching the productivity levels required by the ILRS. The document asks a station to identify what might be limiting its performance and what could make a difference. It then asks the station to outline a plan to increase productivity in the near future. This document was shared with the ILRS Central Bureau, which coordinated sending it out to stations, convening a review committee and putting together feedback to be sent to the stations based on their responses. The first round of stations included a group of 10 stations. A second round of surveys was send to the next 10 stations in April 2025, and the review committee is currently evaluating those responses to later provide feedback to the stations.

A campaign was initiated to track the legacy geodetic satellite WESTPAC, for which ILRS support ended in 2002, to assess if the network could provide regular tracking. Precise predictions were generated by the SGF, Herstmonceux and stations were able to successfully track it during the daytime. Adding this satellite to a station's observing schedule had little impact. WESTPAC returned to the ILRS tracking list officially in March 2023.

NESC met in person at the ILRS Workshop on Laser Ranging in Kunming, China in October 2024. The committee discussed station performance, the ILRS quarantine process and observing campaigns.

7.4 Data Formats and Procedures Standing Committee (DFPSC)

In the years 2023-2025, the DFPSC worked on the following tasks. The ILRS operates two global data and operations centers. To achieve homogeneous data centers, the OCs must apply identical quality checks are already used for incoming SLR measurements. In recent years, the DFPSC has been working together with the ASC to develop quality checks for SINEX products. These checks will be implemented in both OCs, improving the format compliance and file consistency in the future.

An ad-hoc group was created to work with the GGOS Committee of Data and Information Systems (C-DIS). This Committee is implementing GeodesyML, a new standard for handling geodetic metadata. The group, working within the ILRS DFPSC, will provide SLR domain expertise to aid C-DIS in the implementation of GeodesyML for ILRS site logs and possibly other formats specific to the ILRS.

7.5 Space Debris Study Group (SDSG)

The Space Debris Study Group (SDSG), formed in 2014, coordinates laser ranging to space debris and acts as a liaison between the International Laser Ranging Service (ILRS) and international organizations active in this field of research. The SDSG has proposed transitioning to a Space Debris Science and Operations Standing Committee (SDSOSC) to the ILRS Governing Board.

The Graz FTP server plays a crucial role in collecting tracking campaign and experimental space debris laser ranging data for various purposes:

- Orbital Debris Dynamics Analysis: to research interactions of artificial satellites and develop force/torque determination and prediction algorithms [14].
- Time Scale Comparison: Using diffuse bistatic and multistatic laser ranging to tumbling objects like Envisat. This topic is a collaboration subject between European stations [[15], [16], [17], [18]].

- System Upgrades: SDSG members are involved in enhancing SLR stations' space debris laser ranging capabilities and planning for routine use of MHz repetition rate lasers for improved object detection [19].
- Research Outreach and Partnerships through promotion of space debris research in partnership with various organizations. Establishing space debris orbit determination processes helps studying the orbital dynamics of decommissioned satellites and the correlation between their orbital parameters and solar activity. The Graz FTP server regularly provides CPF predictions for better tracking of selected space debris.

The number of stations capable of tracking space debris objects has increased over the last years. They have successfully tested "Stare and Chase" methods for tracking uncooperative targets and published the first successful daylight space debris laser ranging results [20], [21]. Their goal is to achieve 24/7 debris laser ranging using MHz repetition rate lasers. The combined usage of MHz lasers for tracking to cooperative ILRS targets and space debris targets was recently demonstrated improving the precision in both regimes [22].

The SDSG aims to expand on the precision of laser ranging by implementing algorithms to produce attitude state updates for selected tumbling satellites, potentially generating attitude ephemeris tables in CPF format. These tables could be used for studies like detumbling technology analysis, RPO scenarios, and understanding environmental interactions. TOPEX/Poseidon is a primary candidate for this effort due to its fast spin, existing attitude determination methods, and good tracking characteristics [23].

8 Activities of the ILRS Governing Board

The ILRS Governing Board (GB) approved a change to the ILRS Terms of Reference that extended the mandate for elected members to 4 years, renewable. The mandate for the Chair of the Governing Board will be for one 4-year term. The ILRS GB continues to approve missions recommended by the ILRS CB and MSC, and will now also be approving new stations into the ILRS Network, following the recommendation of the ILRS CB and the NESC.

9 ILRS Meetings

Due to unforeseen circumstances, the planned Specialized International Workshop on Laser Raging in Arequipa, Peru for 2023 had to be postponed. We thought it advantageous to give the community an opportunity to get together to discuss updates on pertinent topics, and exchange ideas. The ILRS Virtual International Workshop on Laser Ranging 2023 was held from October 16-20, 2023, with the theme "New Developments in Satellite Laser Ranging", focusing on new materials and new results. Sessions were organized primarily around invited talks, with presentations on new concepts and new technologies. The program and presentations can be access from the ILRS webpages https://ilrs.gsfc.nasa.gov/lw23/index.html.

The Yunnan Observatories and the Chinese Academy of Sciences hosted the 23rd International Workshop on Laser Ranging will be held in Kunming, China during 20-26 October 2024. The hybrid format of the workshop enabled both, in-person and online participation. Access to the program and presentations are available from the following sites https://23rdworkshop.casconf.cn/, and https://23rdworkshop.casconf.cn/page/1858791503279820800.

The first LLR workshop LLR Workshop took place during September 14-15, 2023, at the Pole Astronomie Géoazur, Observatoire de la Côte d'Azur (OCA), CNRS-INSU, Université Côte d'Azur (UCA), France (https://llr2023.sciencesconf.org/). This was the first LLR meeting aimed to bring both the producers, the users and the science behind Lunar Laser Ranging together to join efforts and resources, define goals, and enhance the visibility for a LLR community, identifying synergies and planning for the future, encouraging every group to help, and form a visible global community.

The ILRS Technical Workshop that was planned to take place in Arequipa, Peru in 2025 has now been cancelled. The ILRS is considering options to held virtual meetings to address topics of interest in its place.

The Argentinean CONICET and German BKG (AGGO) in Argentina will be hosting ther 24^{th} IWLR in 2026, as it was decided at the 23rd IWLR in Kunming, China. CONICET offered the venue in the center of Buenos Aires, the Argentine capital.

10 Publications and Reports

The ILRS has contributed to various reports, including the Geodesist Handbook, and the IERS Report. The ILRS CB maintains a comprehensive website as the primary vehicle for the distribution of information within the ILRS community. A list of publications related to the ILRS activities and interests was compiled and continues to be maintained. It is available on the ILRS website (https://ilrs.gsfc.nasa.gov/about/reports/biblio/index.html).

11 Issues and Challenges

Issues and challenges continue as new ground stations become operational and new missions are added to the network roster. Unfortunately, some new stations are deployed near existing stations, thereby improving temporal coverage, but not so much geographic coverage. Organizations like to build new stations close to home to reduce the burden of servicing and upgrading. Overall, we are still suffering from significant gaps in Latin America, Africa, and Oceania and we are seeking additional partnerships to help fill those gaps.

The ILRS stations still include mixes of new and old technologies and still suffers from differences in financial support, lack of standardization, differences in personnel proficiency, and in some cases, insufficient availability of land to allow proper distribution of land calibration targets. These deficiencies and the need to work around them requires extra diagnostic and quality control procedures.

Some stations have suffered long periods of data lapses because of improper monitoring of system conditions. We have tried 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 provided improves station performance, as do on-line data evaluation tools the stations can use. We continue to stress the need for stations to better document their operations and engineering activities and to keep their site logs and history logs up to date. Properly kept logs have revealed operational and procedural issues, and equipment and component failures.

The number of satellite targets continues to increase. In some cases, the ILRS has implemented new tracking strategies to provide increase in volume or orbital variation, or to address satellite vulnerabilities. Improvements in geodetic satellite center of mass corrections continue, and techniques to address sources of data biases have been much improved.

References

[1] Briaud, A., Ganino, C., Fienga, A. et al. (2023) The lunar solid inner core and the mantle overturn. Nature 617, 743–746.

[2] Vishwa Vijay Singh, Jürgen Müller, Liliane Biskupek, Eva Hackmann, and Claus Lämmerzahl (2023) Equivalence of Active and Passive Gravitational Mass Tested with Lunar Laser Ranging, Phys. Rev. Lett. 131, 021401. DOI: https://doi.org/10.1103/PhysRevLett.131.021401

[3] Hu H., Wang Q., Hu H., Zhu H., Dou H. (2024) Comprehensive Overview of the Chang'e-6 Mission: Mankind's Historic First Lunar Farside Sampling and Return, Aerospace china, 7:7-13.

[4] Currie et al. (2024) Next Generation Lunar Retroreflectors and Artemis III, Lunar Surface Science Workshop 22, https://www.hou.usra.edu/meetings/lunarsurface22/pdf/5005.pdf.

[5] Battat, J. B. R., Adelberger, E., Colmenares, N. R., et al. (2023) Publications of the Astronomical Society of the P acific (PASP), 135:104504, DOI 10.1088/1538-3873/aceb2f.

[6] Eckl, Johann (2023) Lunar Laser Ranging at the Geodetic Observatory Wettzell (WLRS), https://ilrs.gsfc.nasa.gov/docs/2023/202309_LLRWS_Grasse_Eckl.pdf.

[7] Chabé, J., Courde, C., Torre, J.-M.,Bouquillon, S., Bourgoin, A.,Aimar, M., et al. (2020). Recent progress in lunar laser ranging at Grasse laser ranging station. Earth and Space Science, 7, e2019EA000785, https://doi.org/10.1029/.

[8] Müller, J., Murphy, T.W., Schreiber, U. et al. Lunar Laser Ranging: a tool for general relativity, lunar geophysics and Earth science. J Geod 93, 2195–2210 (2019). https://doi.org/10.1007/s00190-019-01296-0.

[9] Cacciapuoti, L. et al. (2024) Atomic Clock Ensemble in Space. J. Phys.: Conf. Ser. 2889, 012005.

[10] Schreiber, K. U. et al. (2010) Ground-based demonstration of the European Laser Timing (ELT) experiment. Ultrasonics, Ferroelectrics, and Frequency Control, IEEE Transactions on 57, 728–737.

[11] Takamoto, M. et al. (2020) Test of general relativity by a pair of transportable optical lattice clocks. Nature Photon 6, 1–7.

[12] Wu Z, Geng R, Tang K, et al. (2024) Performance of laser time-frequency transfer system in China Space Station[J]. Acta Optica Sinica.

[13] Geng, Renfang, WU, Zhibo, HUANG, Yong, et al. (2024) A complete analysis of the link uncertainty budget for pulsed laser time transfer on China space station. Advances in Space Research, vol. 73, no 5, p. 2548-2566.

[14] Bennett, J.C., Sang, J., Smith, C.H., et al. Accurate orbit predictions for debris orbit manoeuvre using ground-based lasers. Advances in Space Research (2013)

[15] Sproll, F., Hampf D., Wagner P., et al. Two-color and multistatic space debris laser tracking. 20th Int. Workshop on Laser Ranging (2016).

[16] Hao Sun, Hai-Feng Zhang, Zhong-Ping Zhang and Bin Wu (2015) Experiment on diffuse reflection laser ranging to space debris and data analysis. Research in Astronomy and Astrophysics.

[17] Tong, L., Eckl, J., Steindorfer, M.A., et al. (2021) Accurate ground to ground laser time transfer by diffuse reflections from tumbling space debris objects. Metrologia.

[18] [Wirnsberger, H., Baur, O., Kirchner, G. (2015) Space debris orbit prediction errors using bi-static laser observations. Case study: ENVISAT. Advances in Space Research.

[19] Zhang, H., Li, Y., Li, Z. (2022) Space Debris Laser Ranging with range-gate-free Superconducting Nanowire Single-Photon Detector. J. Eur. Opt. Society.

[20] Steindorfer, M.A., Kirchner, G., Koidl, F., et al. (2016) Stare and chase of space debris targets using real-time derived pointing data. Advances in Space Research.

[21] Steindorfer, M.A., Kirchner, G., Koidl, F., et al. (2020) Daylight space debris laser ranging. Nat Commun.

[22] Steindorfer, M.A., Wang, P., Koidl, F., et al. (2025) Space debris and satellite laser ranging combined using a megahertz system. Nature Communications.

[23] Kucharski, D., Kirchner, G., Bennet, J.C, et al. (2017) Photon Pressure Force on Space Debris TOPEX/Poseidon Measured by Satellite Laser Ranging. Earth and Space Science.