3.4.2 International Laser Ranging Service (ILRS)

Introduction

The International Laser Ranging Service (ILRS), established in 1998, is responsible for the coordination of Satellite Laser Ranging (SLR) and Lunar Laser Ranging (LLR) missions, technique development, network operations, data analysis and scientific interpretation. Here we summarize the status and developments in 2017.

Network

The network of SLR/LLR stations (Figure 1), under the aegis of the ILRS, has been subject to change over the years. In 2017 the network further expanded with the addition of new sites, the majority deployed by Russia, in support of their GLONASS tracking network. From a technical perspective, the quality and quantity of the observations has improved drastically during the past decade. The single-shot precision of an average station today is better than 10 mm (for the best stations this number is a few millimeters, Figure 2). 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. During 2017 the ILRS Central Bureau (CB) made a major effort to encourage all stations to submit for archival their Full Rate (FR) data in addition to their NPs. These data are extremely important in characterizing correctly the response of each system with respect to each target array and calculate the precise correction that connects the ranges to the center of gravity of the target spacecraft, commonly known as the “center-of-mass” correction. Examination of the tracking over the past year indicates that the tracking of targets decreased slightly by about 2.5%, with no change in the number of tracking sites (Table 1 and Figure 8). NASA is moving forward with the deployment of the first next generation Space Geodesy SLR systems (SGSLRs) at McDonald Obs., Texas, to be followed by the one at Mt. Haleakala, Hawaii, and the development of a third system for the Norwegian Mapping Agency, to be deployed at their new core site of Ny-Ålesund, Svalbard. Russia’s expansion and upgrade of their network continues, with new deployment of a system in co-location with MOBLAS 6 at Hartebeesthoek, South Africa, this year actively contributing to the ILRS. All sites will be co-located with GNSS systems primarily intended to tie the GLONASS monitoring network with that of the ILRS SLR. This addition will eventually improve tremendously the tie between the SLR and GNSS-, VLBI-implied frames.

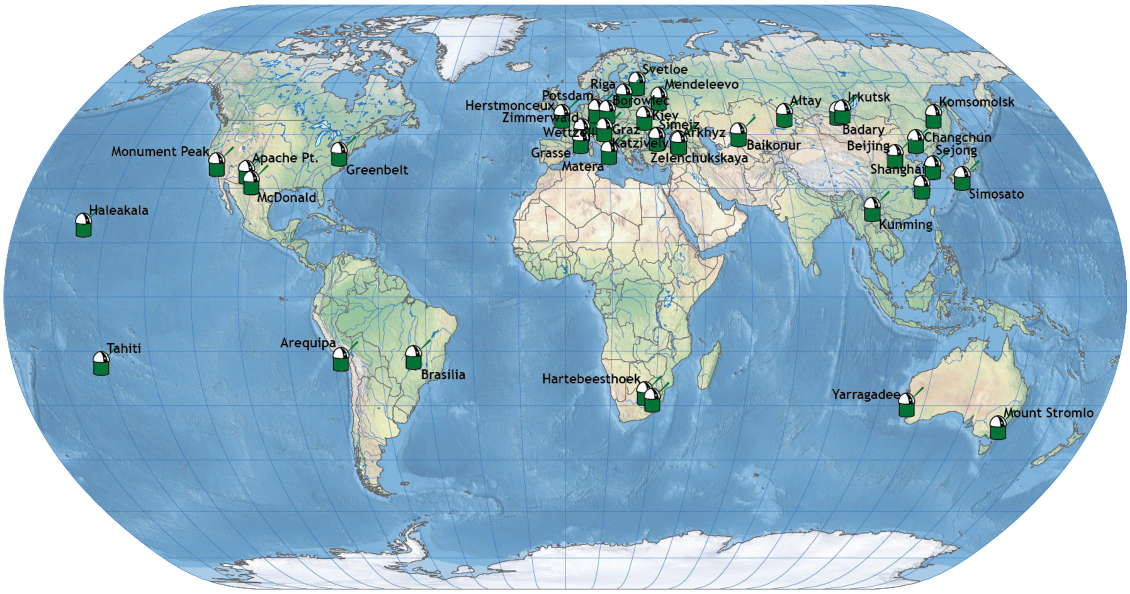


Fig. 1: *The global network of SLR stations (status early 2018).*

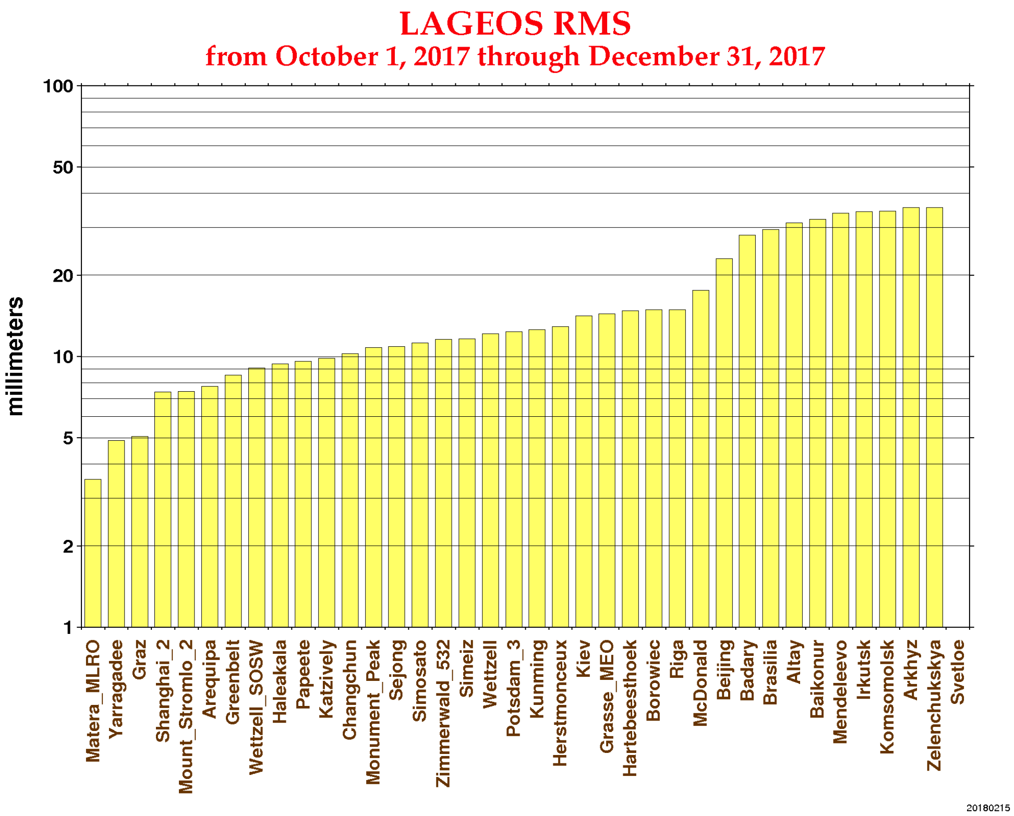


Fig. 2: *: Performance of the global network of SLR stations on LAGEOS (last quarter of 2017).*

Table 1: *ILRS Network Tracking Statistics for 2017*

Site Name	Station	Number of Pass Segments			
		Low	LAGEOS	High	Grand Total
Altay	1879	189	369	2,640	3,198
Arequipa	7403	2,532	217	0	2,749
Arkhyz	1886	444	215	533	1,192
Badary	1890	2,522	255	146	2,923
Baikonur	1887	63	340	1,223	1,626
Beijing	7249	1,523	358	1,365	3,246
Borowiec	7811	432	114	2	548
Brasilia	7407	544	475	1,192	2,211
Changchun	7237	9,022	1,671	6,898	17,591
Grasse	7845	249	459	544	1,252
Graz	7839	3,317	845	2,884	7,046
Greenbelt	7105	5,065	1,273	1,136	7,474
Haleakala	7119	2,435	819	1	3,255
Hartebeesthoek	7501	2,768	1,212	1,419	5,399
Hartebeesthoek	7503	38	37	38	113
Herstmonceux	7840	3,763	1,174	3,606	8,543
Irkutsk	1891	492	170	376	1,038
Katzively	1893	1,693	296	86	2,075
Kiev	1824	339	22	0	361
Komsomolsk	1868	102	201	2,018	2,321
Kunming	7819	885	227	452	1,564
Matera	7941	4,001	2,241	3,938	10,180
McDonald	7080	283	51	2	336
Mendeleevo	1874	169	85	336	590
Monument Peak	7110	5,471	966	1,537	7,974
Mount Stromlo	7825	6,439	1,955	4,259	12,653
Potsdam	7841	3,803	778	573	5,154
Riga	1884	606	109	22	737
Sejong	7394	467	85	3	555
Shanghai	7821	2,117	641	2,744	5,502
Simeiz	1873	1,736	416	181	2,333
Simosato	7838	1,467	595	26	2,088
Svetloe	1888	199	29	15	243
Tahiti	7124	1,078	311	604	1,993
Wettzell	7827	1,344	560	2,404	4,308
Wettzell	8834	3,450	851	2,709	7,010
Yarragadee	7090	22,059	6,251	15,310	43,620
Zelenchukskaya	1889	813	242	309	1,364
Zimmerwald	7810	6,141	1,699	3,725	11,565
Totals:	39 stations	100,060	28,614	65,256	193,930

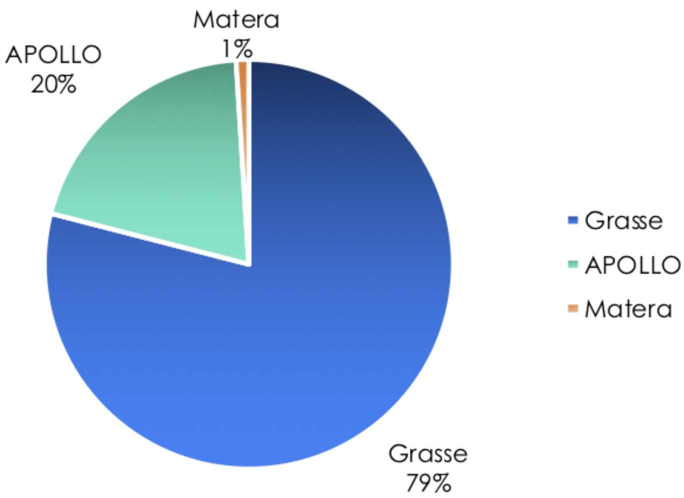


Fig. 3: *Observatory statistics in 2017.*

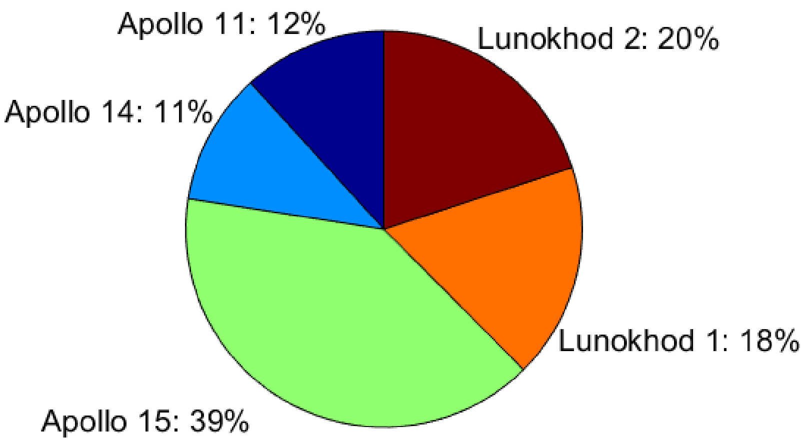


Fig. 4: *Retro-reflector statistics from MeO in 2017.*

Statistics of the SLR data collected as pass segments during the calendar year 2017 are summarized in Table 1. For each of the contributing stations the tracked passes are broken down in three categories of target orbits: Low Earth Orbiters (LEO), LAGEOS 1 & 2 and LARES, and the High Earth Orbiters (HEO), GPS, GLONASS, Etalon 1 & 2, GIOVE-A/B, Galileo, BeiDou, IRNSS, QZSS and the Moon.

Some of the SLR stations are technically equipped to track retro-reflector arrays placed on the surface of the Moon. Currently there are only three Lunar Laser Ranging (LLR) capable stations within the ILRS network of about 40 SLR stations. These are the MeO system of the Observatoire de la Côte d'Azur at Grasse, France, the Matera Laser Ranging Observatory (MLRO) station in Matera, Italy and the non-SLR station

Apache Point Observatory Lunar Laser-ranging Operation (APOLLO) in New Mexico, USA. Additionally, stations Kunming in China (http://english.ynao.cas.cn/research/rp/201801/t20180123_189509.html) and Wettzell in Germany successfully detected lunar returns at the beginning of 2018. Stations in Russia, China and South Africa plan to join the LLR network over the next few years. In 2017, the largest amount of normal points came from the French station in Grasse (79 %), followed by APOLLO (19%) and 35 normal points from MLRO as illustrated in Figure 3. The number of data for 2017 was higher than in any other year of LLR observations. This is mainly due to the successful use of ranging at infrared wavelength at MeO, where most of the data collected in 2017 (~92%) were obtained with infrared instead of the usual green wavelength at 532 nm (http://www.geoazur.fr). Figure 4 illustrates the statistics for the observed retro-reflectors from MeO in 2017 which is representative for the whole data set (The 2017 APOLLO data is not available up to now). Nearly 40 % of the data were obtained from the Apollo 15 reflector array, the Apollo 11 and 14 arrays are measured nearly equally at ~11% and the Lunokhod arrays at ~20%.

LLR data analysis is carried out at a few LLR analysis centers: Jet Propulsion Laboratory (JPL), Pasadena, USA; Center for Astrophysics (CfA), Cambridge, USA; Paris Observatory Lunar Analysis Center (POLAC), Paris, France; and the Institute of Geodesy (IfE) at the University of Hannover, Germany. Recently, the National Institute for Nuclear Physics (INFN), Frascati, Italy, and the Graduate University for Advanced Studies (SOKENDAI), Japan, increased their LLR data analysis activities. One general objective of LLR analysis is to achieve mm-level accuracy; currently this is still at the cm level as seen in Figure 6. The various analysis centers are eager to improve their software codes, though it is a difficult task. Recent activities also comprise simulations to show the potential benefit of improved tracking from additional observatories and/or to new lunar reflectors. These activities are aiming for a better science product, as LLR belongs to the best tools to support lunar science, to study the Earth-Moon dynamics and to test General Relativity in the solar system.

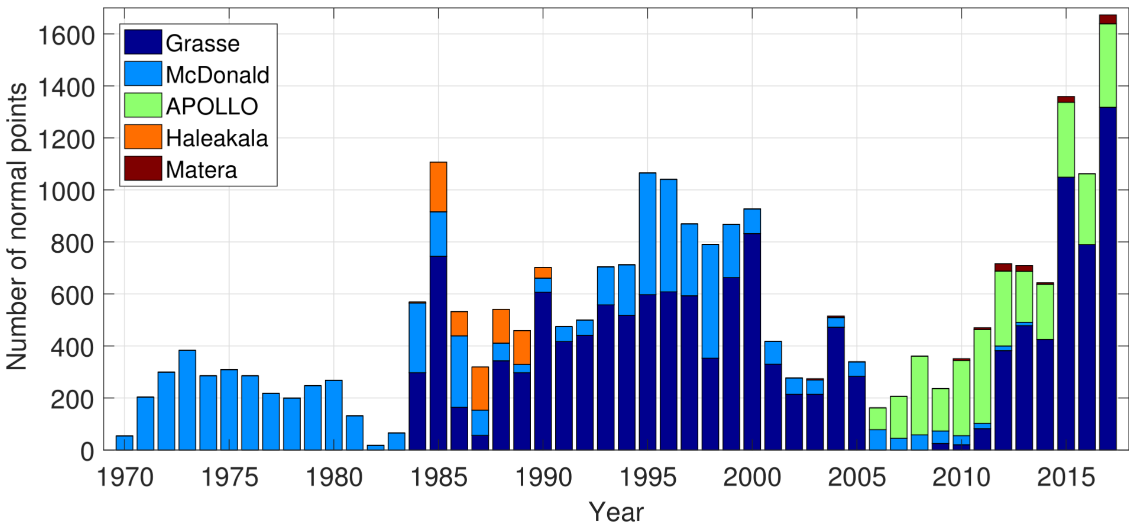


Fig. 5: *Data yield of the global LLR network of stations (up to end of 2017). Note the increased contribution of Grasse's MeO system upon its return to operations in 2011, the steady yield of APOLLO, the small increase at Matera, and the absence of McDonald Obs. the last four years.*

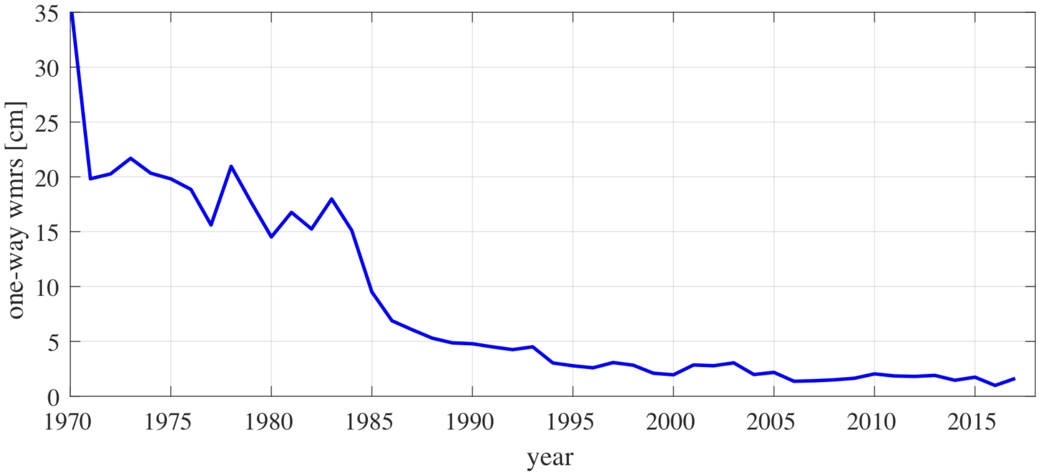


Fig. 6: *LLR residuals, annual WRMS 1970 to 2017.*

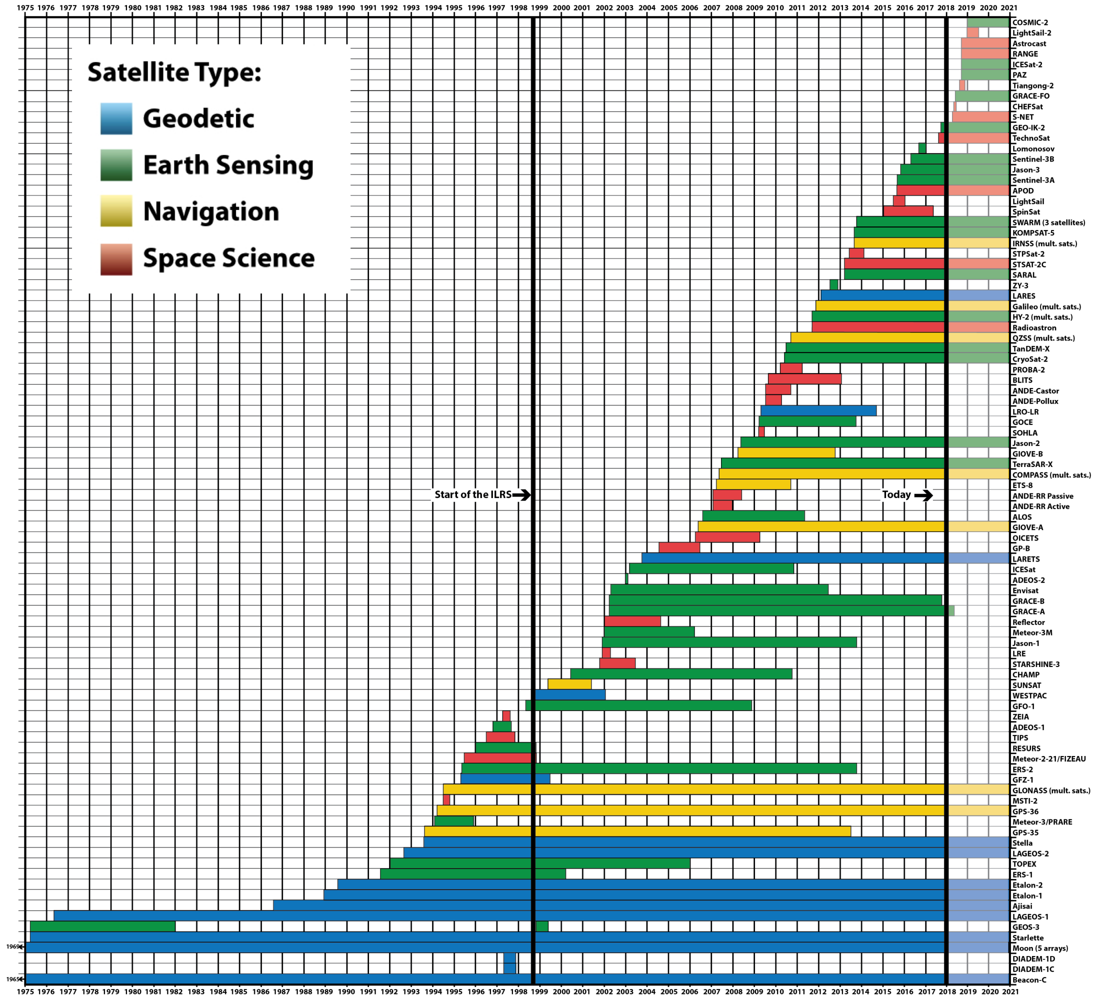


Fig. 7: *The currently tracked SLR missions (status as of late 2017).*

Missions

In 2017, a total of ~100 targets, including those on the moon, were being tracked by SLR/LLR (Figure 7). This indicates a ~42% increase in targets since the 70 missions supported in 2016! Of these, 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 2017 the steady increase of tracking multiple GNSS targets continued for a sixth year in a row and two dedicated tracking campaigns organized through the ILRS/GGOS LARGE Working Group (LAser Ranging to GNSS s/c Experiment), resulted in a substantial increase in data yield from such missions:

- December 19, 2016–March 02, 2017 – Galileo tracking campaign
- January 15–April 15 – LARGE GLONASS tracking campaign
- March 03–April 05 – Galileo tracking campaign
- April 06–May 11 – Galileo tracking campaign

- April 24–May 15 – IRNSS-1B tracking campaign
- May 15–August 15 – LARGE GNSS tracking campaign
- August 25–September 23 – IRNSS-1B tracking campaign
- August 25, 2017–February 28, 2018 – QZS-2 tracking campaign
- November 01, 2017–February 28, 2018 – QZS-3 tracking campaign
- December 01–February 28, 2018 – QZS-4 tracking campaign

Table 2: *ILRS Supported Missions Launched or Initiating Tracking in 2017*

Satellite Name	Satellite ID	SIC Code	Satellite Catalog Number	NP Indicator	Bin Size (sec)	Altitude (Km)	Inclination (°)	First Data Date
Galileo-207	1606901	7207	41859	9	300	23,220	56 +/- 2 °	2017-Feb-16
Galileo-214	1606904	7214	41862	9	300	23,220	56 +/- 2 °	2017-Feb-20
Galileo-213	1606903	7213	41861	9	300	23,220	56 +/- 2 °	2017-Feb-20
Galileo-212	1606902	7212	41860	9	300	23,220	56 +/- 2 °	2017-Feb-20
QZS-2	1702801	1582	42738	9	300	32,000-40,000	45 °	2017-Jun-01
TechnoSat	1704205	6203	42829	3	15	600	97.6 - 97.9 ° +/- 7.2 '	2017-Jul-30
QZS-3	1704801	1583	42917	9	300	36,000	0 °	2017-Sep-12
QZS-4	1706201	1584	42965	9	300	32,000-40,000	45 °	2017-Oct-12
GLONASS-137	1705501	9137	42939	9	300	19,140	65 °	2017-Oct-16
Geo-IK-2	1603401	5561	41579	5	30	943.5 - 973.5	99.47 °	2017-Oct-18

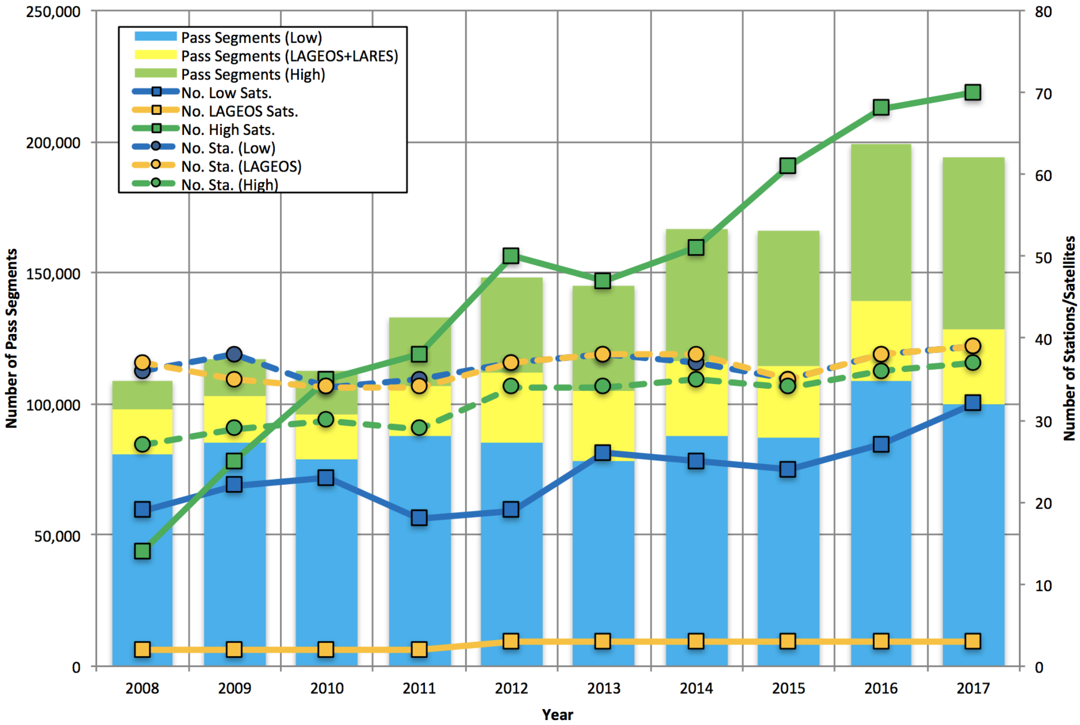


Fig. 8: *ILRS network data yield by target type since 2008 and up to the end of 2017.*

During 2017 the new missions that were launched are shown in Table 2. All but two were spacecraft of GNSS Constellations. We also had the end of one mission: SpinSat re-entered the Earth's atmosphere on March 11, 2017. Finally, this year, the Italian Space Agency (ASI) approved the development of the LARES-2 spacecraft, very much in shape along the lines of LARES, however, slightly larger, heavier and to be placed in orbit thanks to an offer by ESA, on the maiden launch of the extended VEGA (C) rocket sometime in late 2019 (Ciufolini et al., 2017). Despite the increase in the number of targets in 2017, the ILRS network has increased its productivity to keep pace with this increased demand for support, and kept the data yield at similar levels as in the past years (Figure 8).

Analysis and science

The effort to identify, mitigate and monitor systematic errors in the ILRS data has continued-on since several years with new initiatives and results. The Pilot Project to develop a strategy for a combined product that delivers estimates of station systematics on a regular basis led to the development of an operational tool. Initially a re-analysis of the main ILRS targets LAGEOS and LAGEOS-2 was completed, (eventually it will include Etalons and LARES), covering all SLR data from 1993 to present. The reanalysis followed the established best practice to monitor separately the systematics on each s/c and to allow for long-term averaging of the results of weekly estimates. This will now transition to a fully operational product that will become available in 2018, once a trial period with the participation of all ILRS ACs is successfully completed. The weekly estimates from a preliminary combination at the JCET Combination Center were averaged over the 25-year period to obtain a reliable mean estimate for each target separately (Figure 9). These averaged results along with the individual AC estimates are displayed in Figures 10 (a)-(d) separated into biases above and below the 10-mm threshold.

A dedicated web-portal was developed to allow numerous ways of comparing the results between different ACs, targets and time intervals: http://geodesy.jcet.umbc.edu/BIAS_W_v221/configuration.php Example results of the reanalysis for two specific systems and all ACs for LAGEOS 1 over the period 1993-2018 are displayed in Figure 11 at Yarragadee, Australia, (a), and Matera, Italy, (b). Note that in general, the results are all very close to each other, indicating the high degree of consistency between the individual ACs' analysis.

The next phase of the project is the development of this product as a service to the network, so that stations can be notified when an abnormal estimate is obtained. The process requires careful implementation to limit false alarms and for that we first needed to develop a long history of the systematics for each station separately. This task was completed in 2017, and the operational service will be in test mode during early 2018.

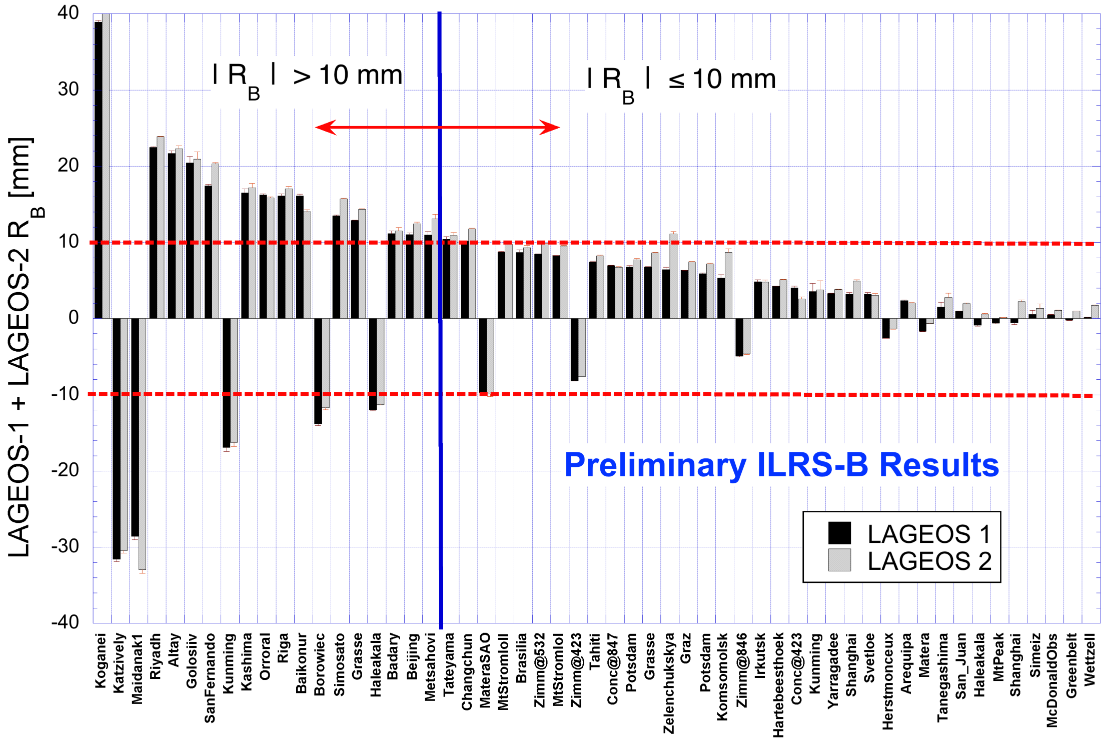
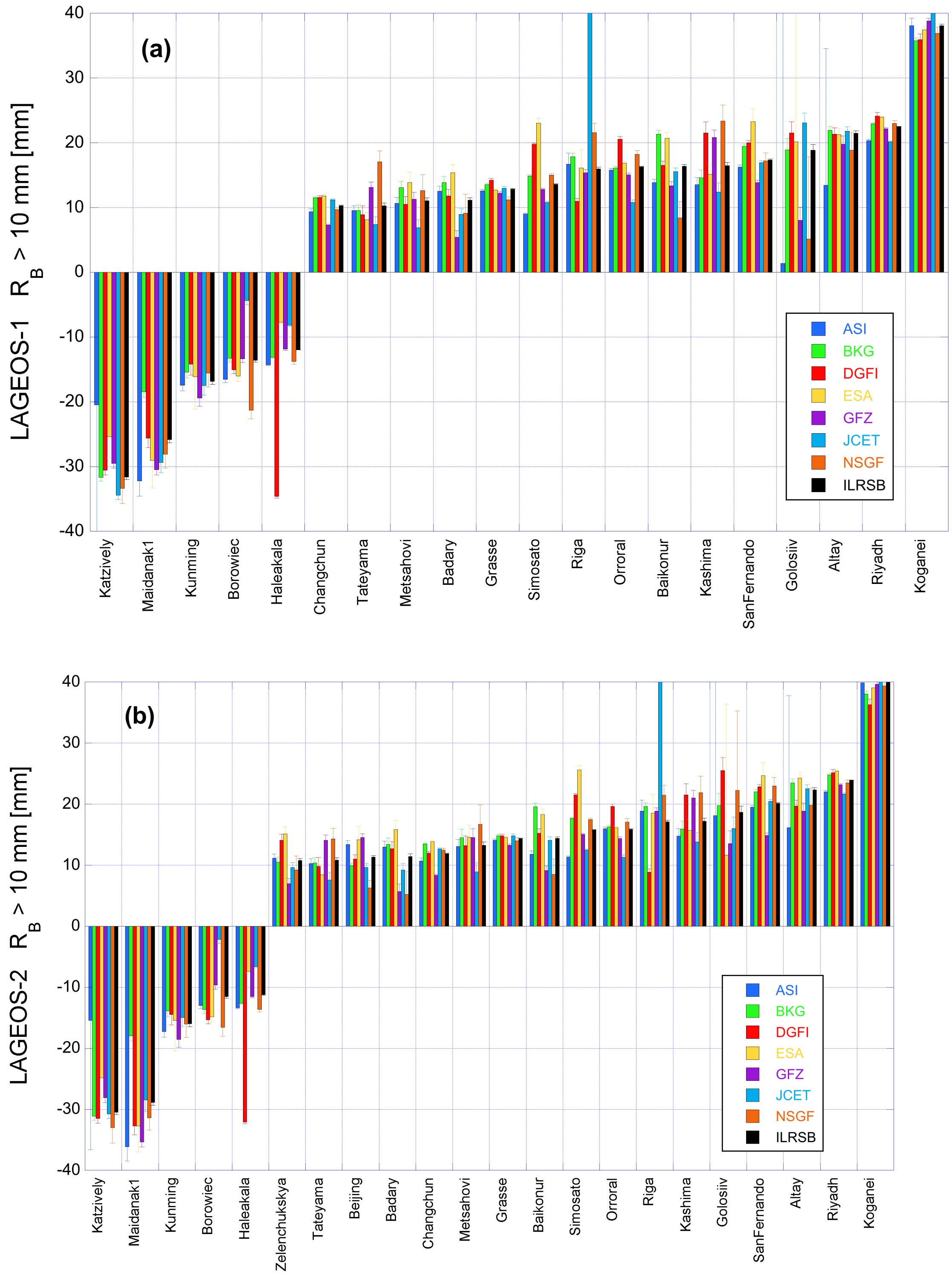


Fig. 9: *Mean range bias estimates for each of the LAGEOS s/c and all ILRS stations that contributed data to the SSEM Pilot Project, averaged over the period 1993-2018 (~1305 weeks). A more detailed analysis in the final phase will separate the time interval to allow for changes in the mean bias, due to observed jumps and station position changes.*


(a)
LAGEOS-1 R_B > 10 mm [mm]
40
30
20
10
0
-10
-20
-30
-40
Katzively
Maidanak1
Kunming
Borowiec
Haleakala
Changchun
Tateyama
Metsahovi
Badary
Grasse
Simosato
Riga
Orroral
Baikonur
Kashima
SanFernando
Golosiiv
Altay
Riyadh
Koganei
ASI
BKG
DGFI
ESA
GFZ
JCET
NSGF
ILRSB
(b)
LAGEOS-2 R_B > 10 mm [mm]
40
30
20
10
0
-10
-20
-30
-40
Katzively
Maidanak1
Kunming
Borowiec
Haleakala
Zelenchukskya
Tateyama
Beijing
Badary
Changchun
Metsahovi
Grasse
Baikonur
Simosato
Orroral
Riga
Kashima
Golosiiv
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NSGF
ILRSB

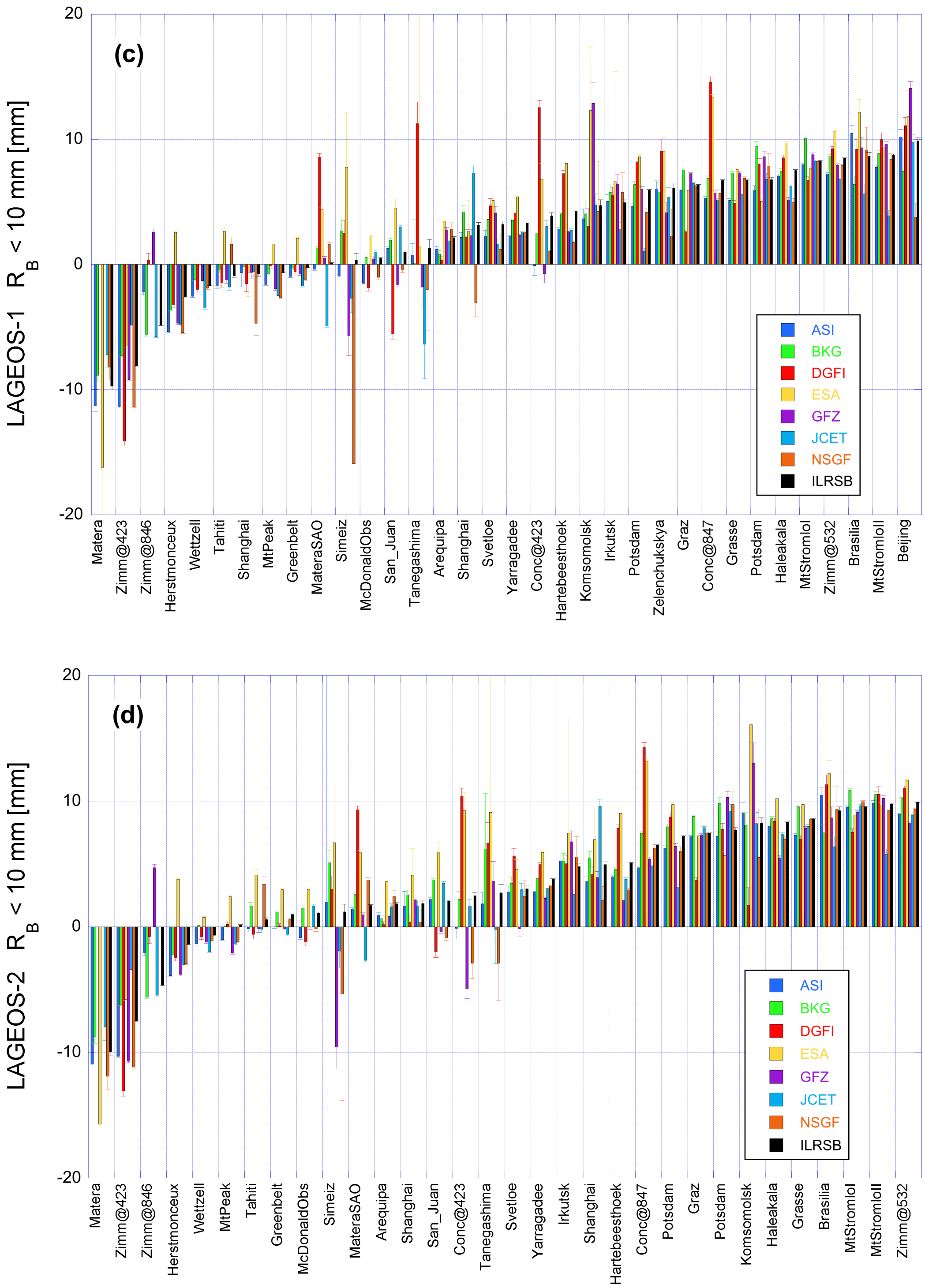

Fig. 10: *The systematics for the ILRS network, averaged over the period 1993 – 2018, for each target separately, LAGEOS 1 top figures (a) and (c), and LAGEOS 2 bottom figures (b) and (d). Preliminary results from the Station Systematic Error Monitoring Pilot Project ordered by the magnitude of the combined ILRS-B estimate for each case. The results are organized in two groups for each target satellite, those with a bias magnitude over 10 mm, (a) and (b), and those with an estimate below that threshold value, (c) and (d).*

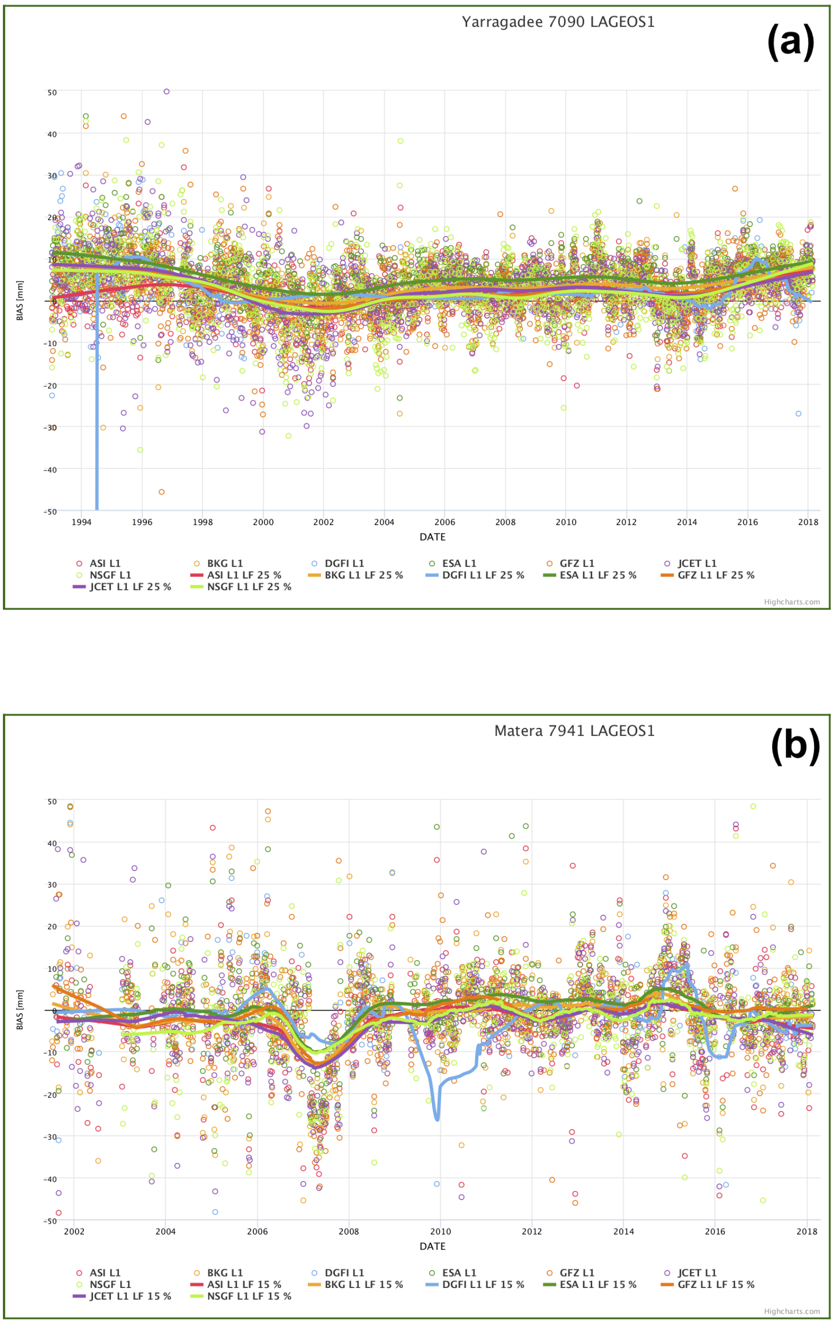

Fig. 11: *Weekly estimates of the systematic error for (a), the Yarragadee, Australia, (7090) and (b), the Matera, Italy MLRO system (7941). The circles indicate the weekly results while the lines are a "moving average" LOESS estimate.*

Meetings

In 2017 the ILRS held a Technical Workshop at Riga, Latvia, during the week of October 2–5, hosted by the Institute of Astronomy at the University of Latvia. The theme for this workshop was: "Improving ILRS Performance to Meet Future GGOS Requirements" and the topics that were addressed:

- What are the current and anticipated laser ranging requirements for the various satellites and have we defined them properly?
- How do we evaluate our current performance and is it adequate?
- What factors are currently limiting our network performance?
- What operational steps and tools would help us to better meet satellite ranging accuracy and scheduling requirements?
- What automation capabilities have been implemented or are planned for implementation, and what automation capabilities should stations consider?

The workshop was very well attended with over 120 participants from many countries, more than 50 oral presentations and many poster presentations. The ASC held two meetings in 2017, one during the EGU General Assembly, on April 22 (http://ilrs.gsfc.nasa.gov/science/awg/awgActivities/index.html), and one prior to the Riga Workshop, on October 1 (http://ilrs.gsfc.nasa.gov/science/awg/awgActivities/index.html). The ILRS Governing Board met once in 2017, prior to the Riga workshop on October 1 (http://ilrs.gsfc.nasa.gov/about/organization/govboard/gbmeeting_reports.html). In 2018 the ILRS will hold the 21st International Workshop on Laser Ranging that will take place in Canberra, Australia, November 5–9. For more information please see:

http://www.iwlr2018.serc.org.au

The topic of the 2018 Workshop is: “Laser Ranging for Sustainable Millimeter Geoscience".

Publications

Access all the presentations, posters, and proceedings papers presented at the Technical Workshop in Riga from the official ILRS page for the workshop:

https://cddis.nasa.gov/2017_Technical_Workshop

An extensive list of general publications of interest to ILRS associates can be found at the ILRS website:

http://ilrs.gsfc.nasa.gov/about/reports/biblio/bibliography.2017.html

References

Ciufolini, I., Paolozzi, A., Pavlis, E. C., Sindoni, G., Koenig, R., Ries, J. C., Matzner, R., Gurzadyan, V., Penrose, R., Rubincam, D., others (2017). A new laser-ranged satellite for General Relativity and space geodesy: I. An introduction to the LARES2 space experiment. *Eur. Phys. J. Plus (2017) 132: 8, 336. urlhttps://doi.org/10.1140/epjp/i2017-11635-1.*

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