3.4.3 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 2019.

Network

The network of SLR/LLR stations (Figure 1), under the aegis of the ILRS, has been subject to change over the years. In 2019, the network remained very much in its past year's form. The only significant change was the introduction of a new system (laser) at the old Wuhan site in PR of China. From a technical perspective though, the quality and quantity of the observations has improved drastically during the past few years. 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 2019, the ILRS Central Bureau (CB) continued its efforts 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 targets increased by $\sim$20% while the collected pass segments increased by $\sim$13%, 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 the announcement of future deployment of a new system in co-location with the current one at Irkutsk and Mendeleevo in the coming year. All sites will be co-located with GNSS systems primarily intended to tie the GLONASS monitoring network with that of the ILRS SLR.

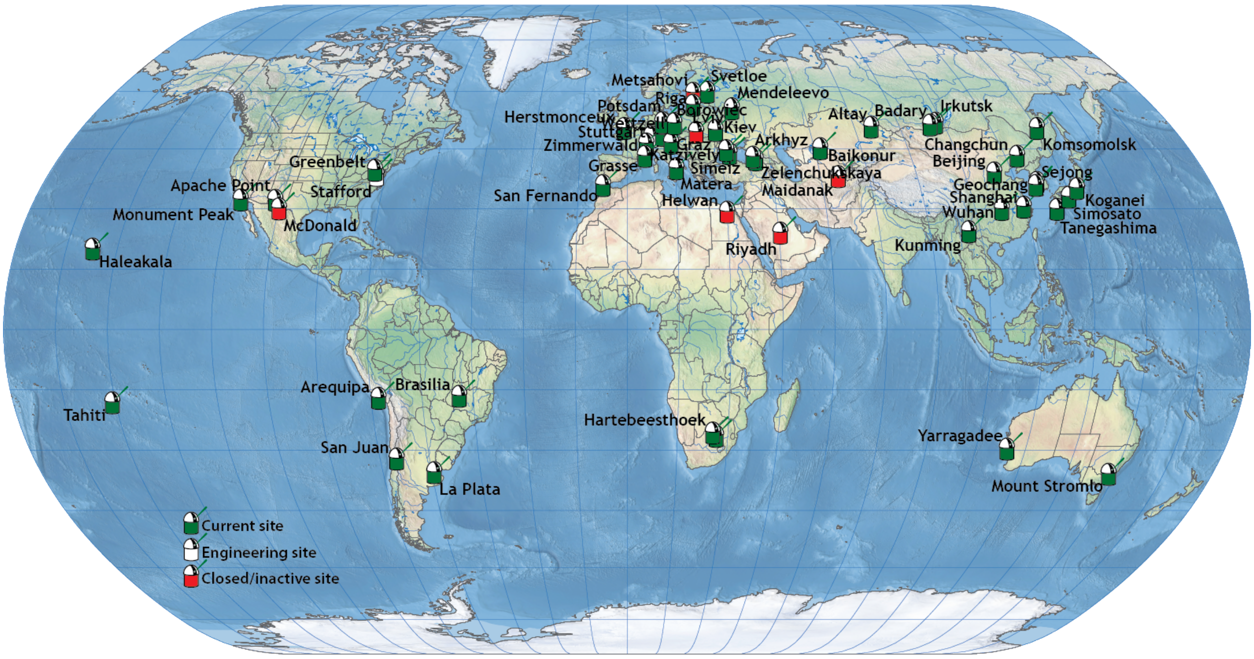

Fig. 1: *The global network of SLR stations (status late 2019).*

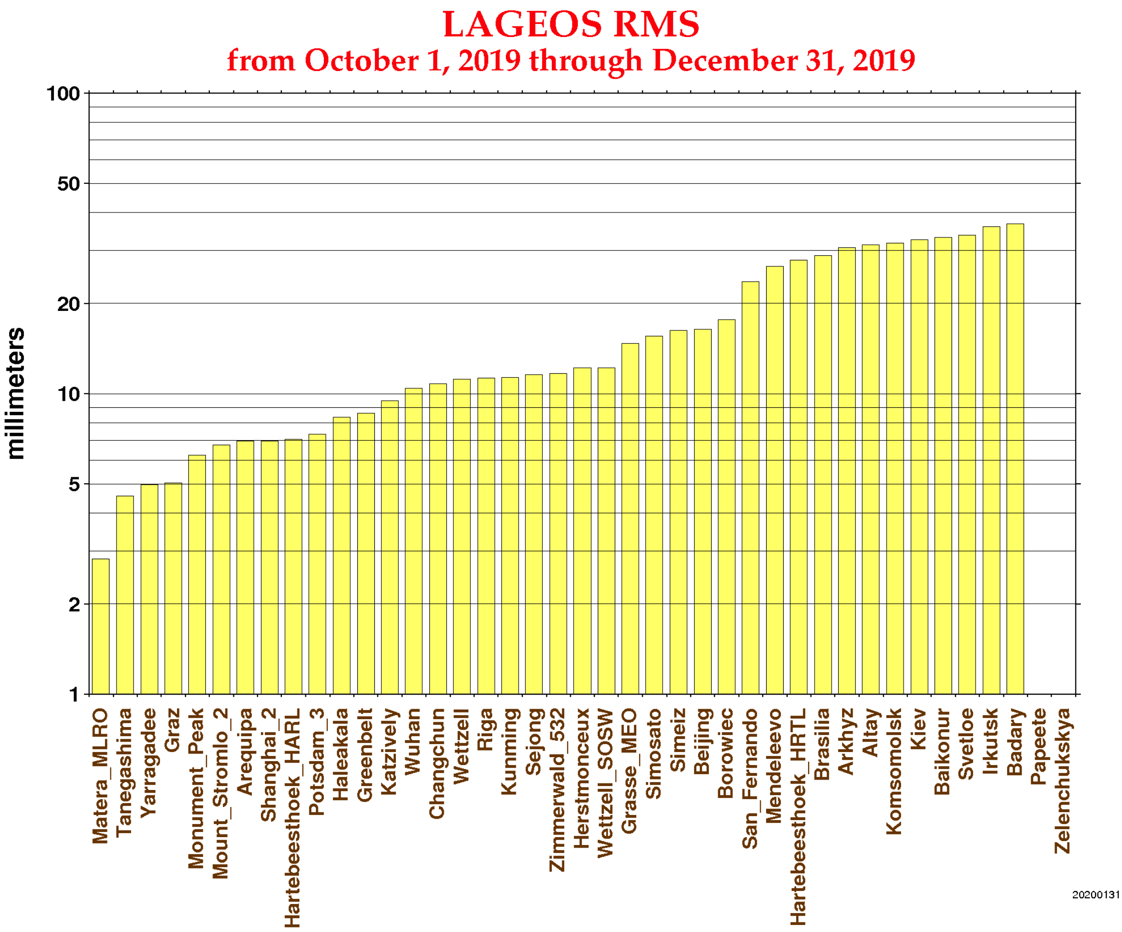

Fig. 2: *Performance of the global network of SLR stations on LAGEOS (last quarter of 2019).*

Table 1: *ILRS Network Tracking Statistics for 2019*

Site Name	Station	Low	LAGEOS	High	Grand
Altay	1879	61	273	1,769	2,103
Aueqripa	7403	3,722	194	0	3,916
Arkhyz	1886	550	363	622	1,535
Badary	1890	1,749	676	499	2,924
Baikonru	1887	0	416	594	1,010
Beijing	7249	1,546	368	1,355	3,269
Borowiec	7811	769	211	77	1,057
Brasilia	7407	181	278	916	1,375
Changuhcn	7237	8,895	1,294	5,585	15,774
Grasse	7845	262	676	3,034	3,972
Graz	7839	3,937	751	3,374	8,062
Greeneblt	7105	6,246	1,401	1,202	8,849
Haleaakla	7119	2,543	702	0	3,245
Hartebeesthoek (NASA)	7501	3,753	1,095	1,715	6,563
Hartebeesthoek (Russia)	7503	1,092	402	1,169	2,663
Herstmonceux	7840	5,591	1,268	3,738	10,597
Irkutsk	1891	1,340	245	402	1,987
Katzively	1893	1,961	357	6	2,324
Kiev	1824	783	87	0	870
Komsomolsk	1868	35	252	1,594	1,881
Kunming	7819	4,108	966	5,858	10,932
Matera	7941	3,791	1,534	2,390	7,715
Mendeleevo	1874	64	71	128	263
Monument Peak	7110	5,801	509	615	6,925
Mount Stromlo	7825	7,507	1,454	1,970	10,931
Potsdam	7841	3,003	608	1,408	5,019
Riga	1884	611	194	102	907
San Fernando	7824	55	166	0	221
Sejong	7394	238	59	1	298
Shanghai	7821	2,921	811	3,406	7,138
Simeiz	1873	2,206	521	411	3,138
Simosato	7838	815	157	7	979
Svetloe	1888	891	330	195	1,416
Tahiti	7124	304	63	93	460
Tanegashima	7358	26	151	0	177
Wettzell (SOS-W)	7827	3,194	987	4,132	8,313
Wettzell (WLRS)	8834	4,903	1,602	3,744	10,249
Wuhan	7396	428	150	672	1,250
Yagraradee	7090	29,455	5,405	13,024	47,884
Zelenchukskaya	1889	285	55	88	428
Zimmerwald	7810	8,278	1,909	3,962	14,149
Totals:	41	123,900	29,011	69,857	222,768

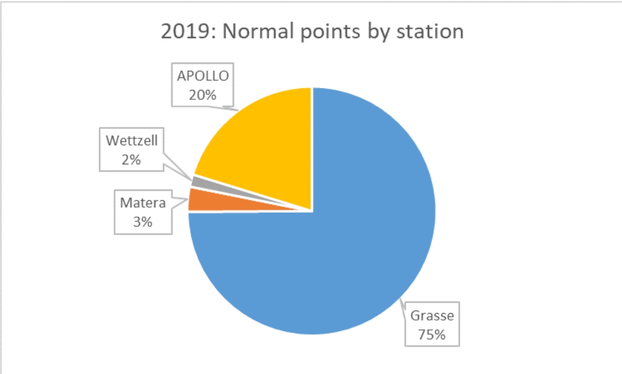

Fig. 3: *Observatory statistics in 2019.*

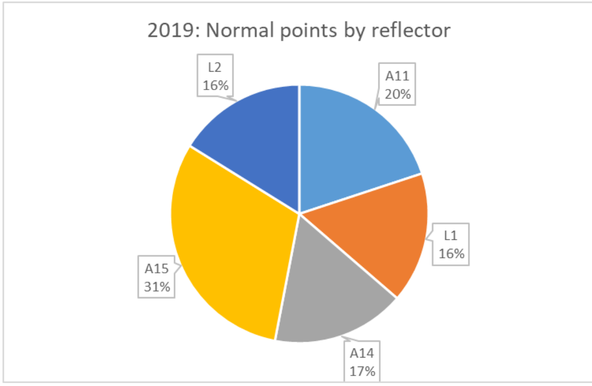

Fig. 4: *Retro-reflector statistics by reflector in 2019.*

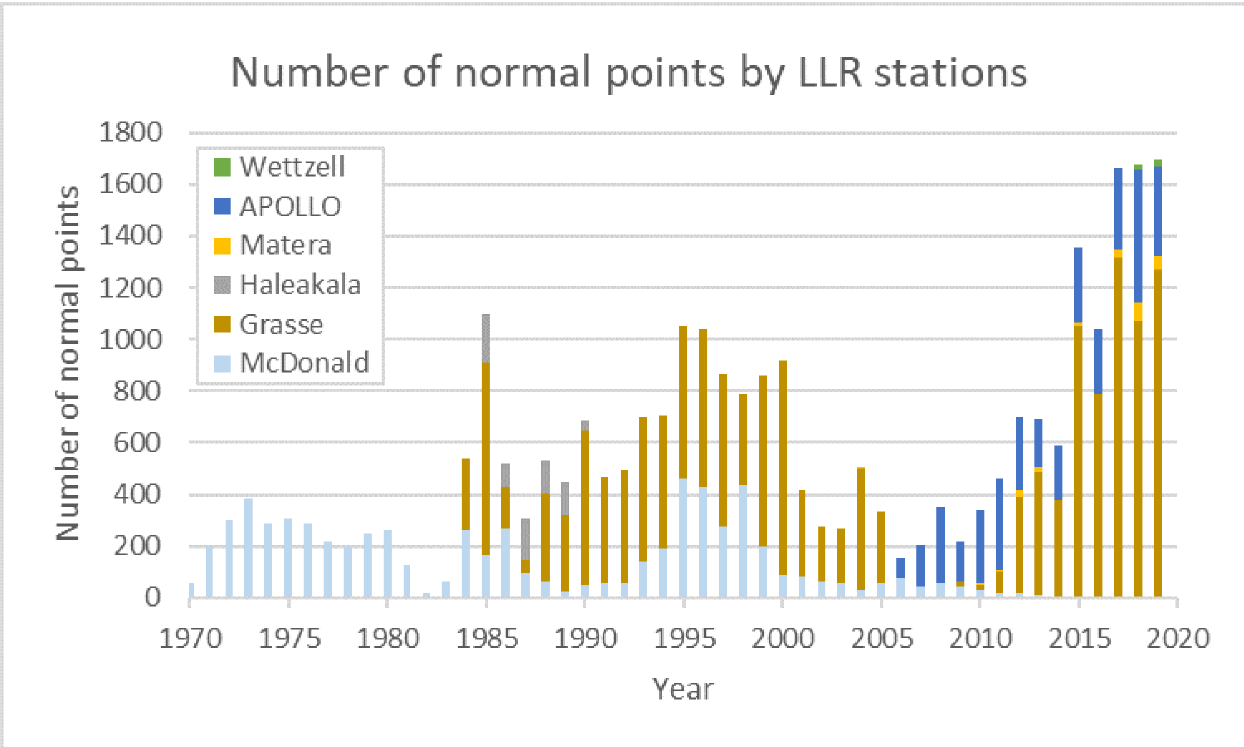

Fig. 5: *Data yield of the global LLR network of stations (up to end of 2019). Note the increased contribution of Grasse's MeO system since 2016, a steady yield of APOLLO, small increase at Matera and welcome Wettzell! McDonald LLR Obs. officially shut down at the end of 2019.*

Statistics of the SLR data collected as pass segments during the calendar year 2019 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 (MEO), 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 four Lunar Laser Ranging (LLR) capable stations within the

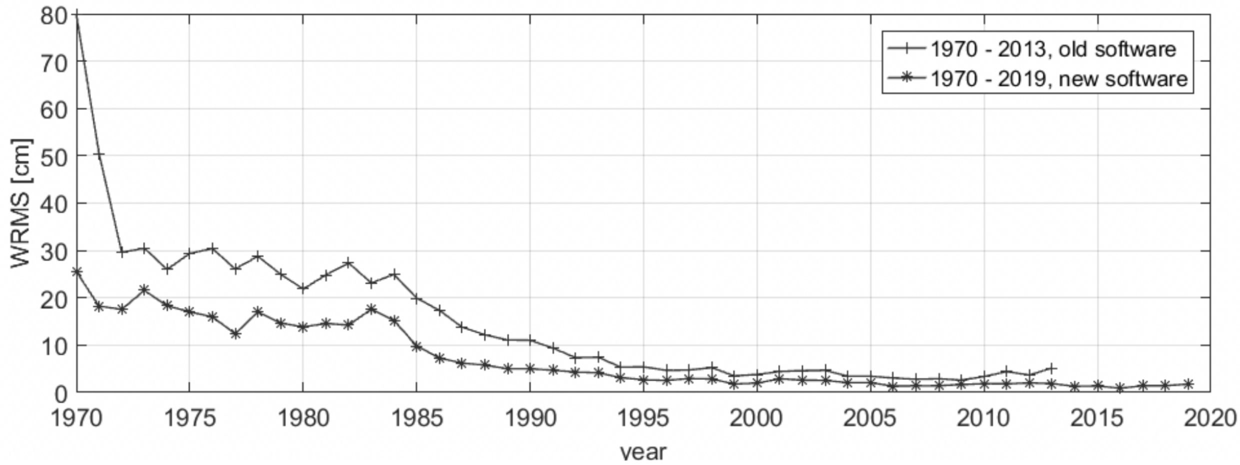

Fig. 6: *LLR residuals, University of Hannover's IfE multiyear analysis, annual WRMS 1970 to 2019.*

ILRS network of about 40 SLR stations. These are the Grasse station (MeO) in France, the Matera station (MLRO) in Italy, the Wettzell station (WLRS) in Germany, and the non-SLR station Apache Point Observatory Lunar Laser-ranging Operation (APOLLO) in New Mexico, USA. Additionally, Kunming station, belonging to the Yunnan Observatories, in Popular Republic of China (http://english.ynao.cas.cn/research/rp/201801/t20180123_189509.html), successfully detected lunar returns since the beginning of 2018. Stations in Russia (Altay), China and South Africa plan to join the LLR network over the next few years.

Although data have been taken on the Apollo 11, 14, and 15, and the Lunokhod 1 and 2 reflectors, the bulk of the data has been from the largest reflector array, Apollo 15. In the next few years, a new generation of reflectors, more accurate and more efficient, are expected to be deployed on the Lunar surface. After the 2018 initial tests at MeO with 2-way ranging in infrared to the Lunar Reconnaissance Orbiter-LRO, the next significant ranging sessions were collected in August of 2019, with the results highlighted in Mazarico et al. (2020). This experiment demonstrated routine 2-way ranging to a spacecraft at lunar distance. 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

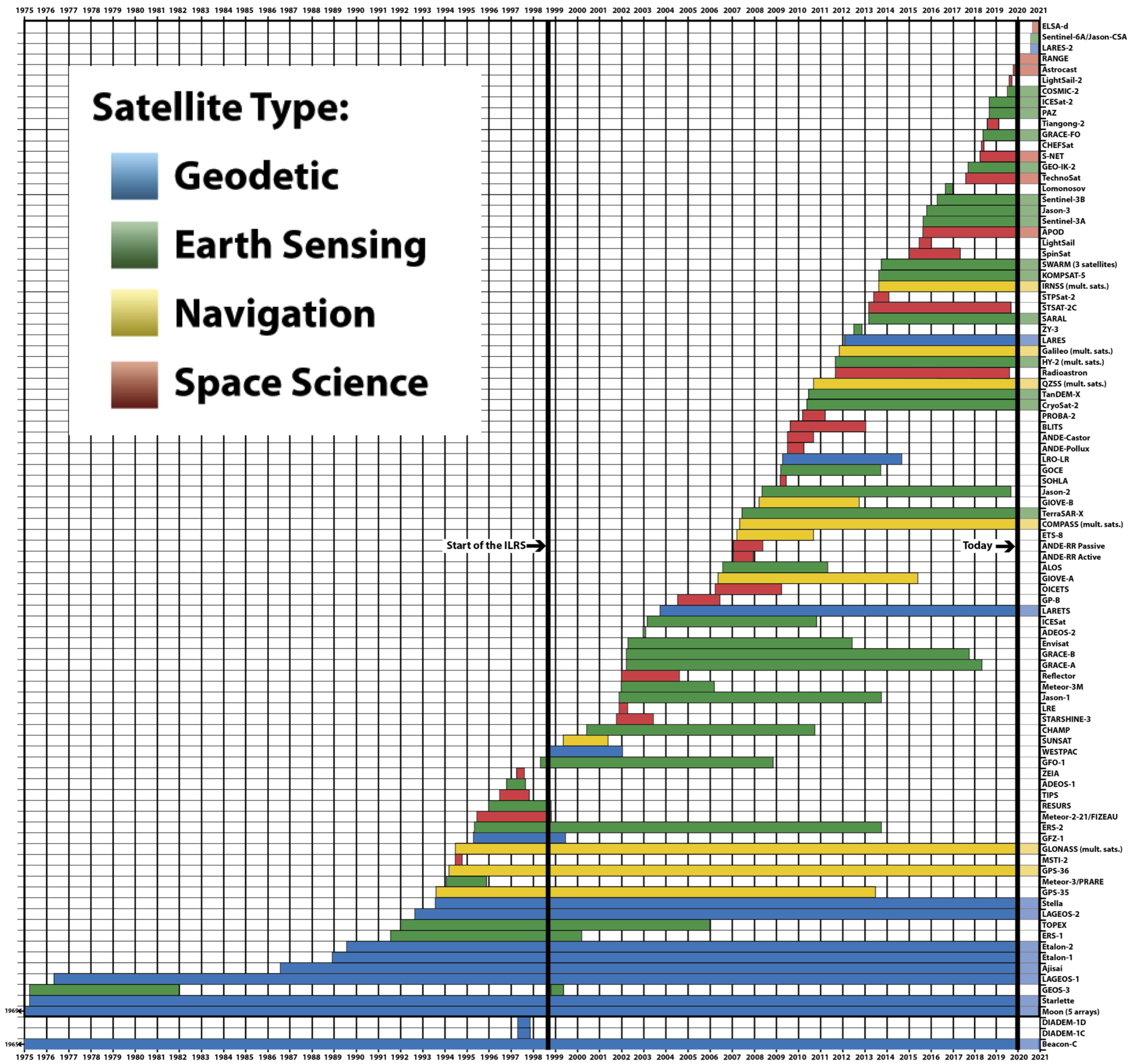

Fig. 7: *The currently tracked SLR missions (status as of early 2020).*

use. In addition, various research projects have been successfully run combining LLR, GRAIL, and LRO data.

During the last few years, the strong increase in the annual LLR normal point rate was mainly due to the effort at the French station in Grasse (Courde et al., 2017). The total data archive is still dominated by the Apollo 15 reflector, but its impact was reduced and for the period between 2016 and 2018 (Fig. 4) the contribution from the smaller reflectors has increased with the Apollo 15 share down to 30%. It should be noted however, that the data count from the APOLLO site is known approximately, since the exact number of normal points after 2016 have not been distributed to date and could only be guesstimated in the Figures 3–5.

LLR is an important tool to support lunar science, to study the Earth-Lunar dynamics and to test General Relativity in the solar system. Current improvements in the estimation of relativistic parameters include, e.g., tests of the equivalence principle, possible time variability of the gravitational constant and Lorentz symmetry (Hofmann and Müller, 2018). LLR based EOP results contribute to combined EOP solutions. With the larger LLR data set over time the lunar tidal acceleration has been more accurately determined (Williams and Boggs, 2016) as well as station coordinates and velocities. Through the studied of lunar tides, physical librations and the lunar orbit, LLR has been an important tool in improving our understanding of the physical properties and the interior of the moon. Discrepancies between LLR and GRAIL derived results (Pavlov et al., 2016) of elasticity parameters (Love numbers) and the degree-3 gravitational field which leads us to recognize that there is still very interesting and challenging science to address, especially in the modelling of dissipation and properties of the lunar interior.

Missions

In 2019, a total of 120 targets, including those on the moon, were being tracked by SLR/LLR (Figure 7). 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 2019 the steady increase of tracking multiple GNSS targets continued at the same pace as in 2018. The launch of the GRACE Follow-On mission resulted in the initiation of a tracking campaign in late 2018, which was finalized in 2019:

- *December 15, 2018–January 15, 2019 – GRACE-FO tracking campaign*
- *February 15–May 15 – Etalon campaign of 2019*

The data collected during the campaign were examined and compared to prior years. The analysis of these data indicated the improvement of EOP products and the findings were summarized in the Etalon campaign report.

Table 2: *ILRS Supported Missions Launched or Initiating Tracking in 2018*

Satellite Name	Satellite ID	SIC Code	Satellite Catalog Number	NP Indicator	Bin Size (s)	Altitude (km)	Inclination (°)	First Date Tracked
GLONASS-141	1908801	9141	44850	9	300	19,140	65	2019-12-11
GLONASS-140	1903001	9140	44299	9	300	19,140	65	2019-07-03

Table 3: *ILRS Supported Missions that Completed their Operations in 2019*

Satellite Name	Satellite ID	SIC Code	Satellite Catalog Number	NP Indicator	Bin Size (s)	Altitude (km)	Inclination (°)	Last Date of Data
LightSail-2	1903629	4202	44420	3	15	720	24	2019-09-20
Jason-1	0105501	4378	26997	3	15	1336	66	2019-09-12
Tiangong-2	1605701	2207	41765	1	1	350-400	42	2019-01-03

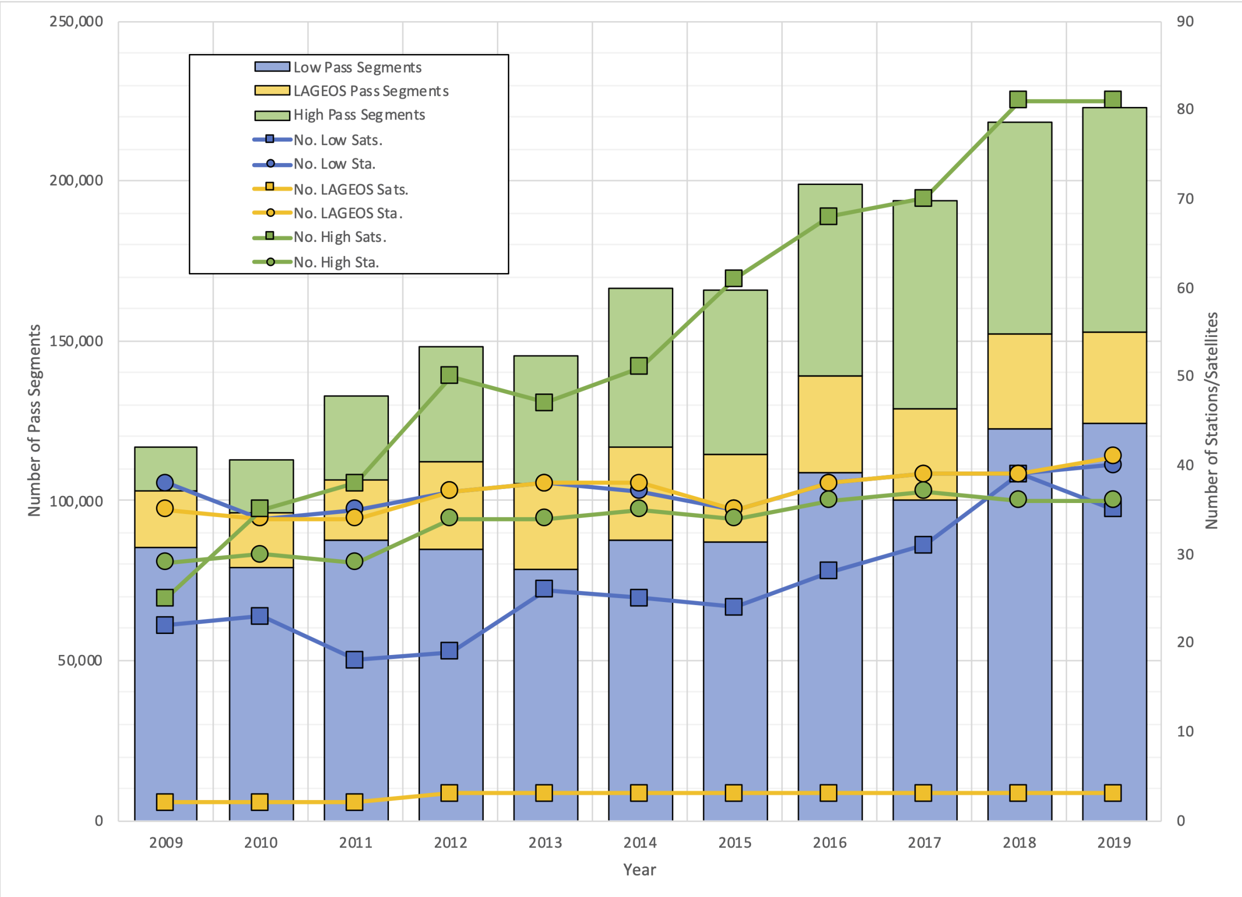

Fig. 8: *ILRS network data yield by target type since 2009 and up to the end of 2019.*

Analysis and science

A new re-analysis of the data from the main ILRS targets LAGEOS, LAGEOS-2 and the two Etalons was completed in 2019. The results of the 2018 reanalysis indicated clearly that the response from these targets was not modeled sufficiently accurately, resulting in significant systematic errors. The re-analysis revealed serious shortcomings in the "target signature" model (aka "center of gravity"-CoG correction), so a new model was developed (Rodríguez et al., 2019), leading to significant changes. The improved model benefited from new and verified information about the ground tracking systems' mode of operation and utilized hardware, delivering improved results across the entire network and for a significant portion of the recent tracking history. The regenerated combined series from 1993 to present resulted in revised long-term mean biases for the entire network demonstrating an improved, more random distribution with significantly reduced magnitudes at all stations (Figure 9). These revised preliminary results are very promising because they imply that the new SLR scale is significantly closer to that implied by VLBI, diminishing the gap between the two techniques to 0.24 ppb. When the re-analysis is completed the new approach will transition to a fully operational product that will become the standard mode for ILRS analysis products.

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 weekly 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. Once this task is completed the operational service will become operational following the development of ITRF2020.

Meetings

In 2019 the ILRS held a Technical Workshop on Laser Ranging that took place in Stuttgart, Germany, October 21–25. For more information please see:

https://ilrsworkshop2019.besl-eventservice.de

The topic of the 2019 Technical Workshop was: "Laser ranging: To improve economy, performance, and adoption for new applications". The workshop included for the first time the very successful "First One-day Introductory and Refresher Course on Satellite and Lunar Laser Ranging", with tutorials for novices as well as SLR experts on many subjects, which was widely attended. The workshop was very well attended as well, with over 150 participants from many countries.

The ASC held two meetings in 2019, one prior to the 2019 EGU General Assembly in Vienna, Austria, on April 6, and one prior to the GGOS/IERS Unified Analysis Workshop, on October 1, in Paris, France. The ILRS planned ahead to hold future meetings in 2020 and 2021, however, due to the pandemic these have been now postponed. In

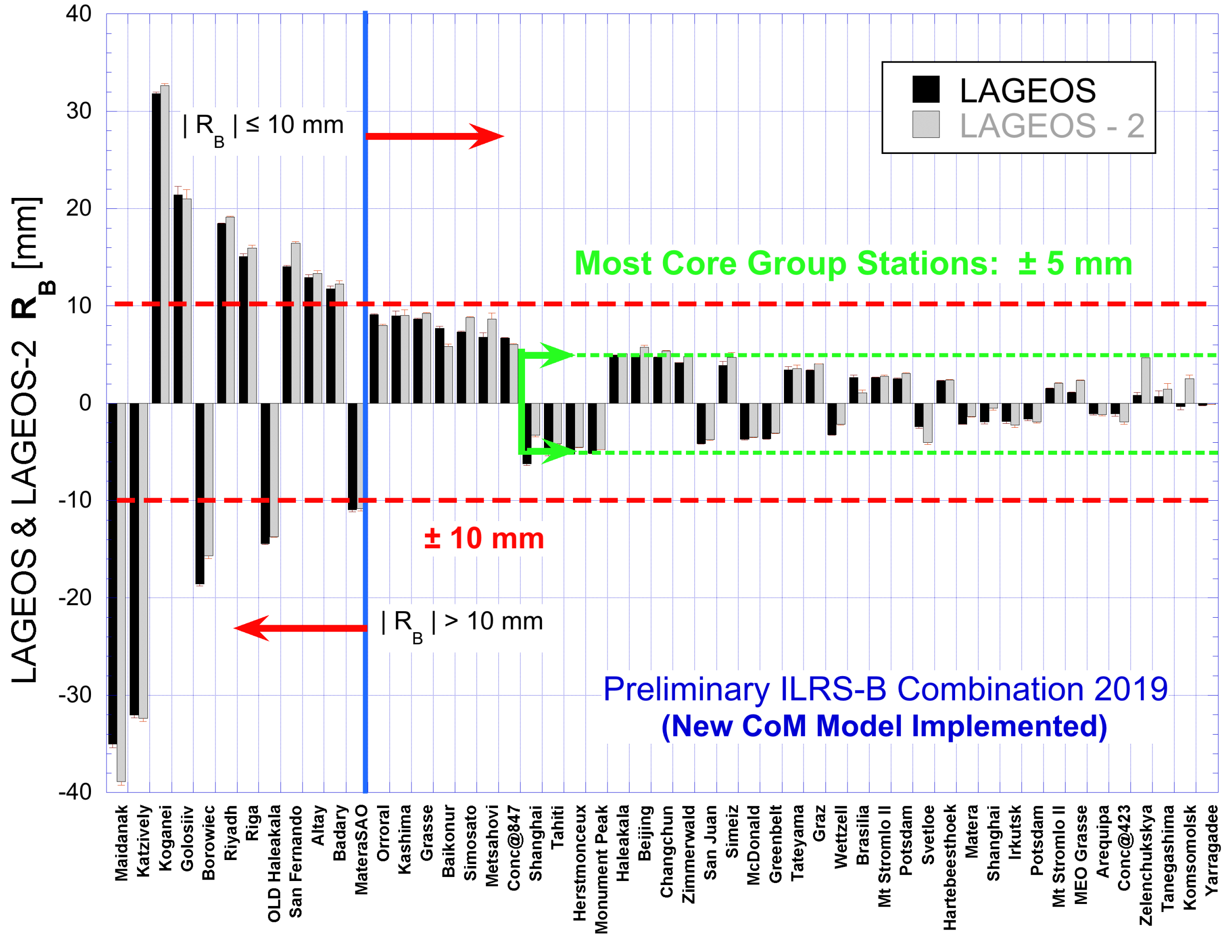

Fig. 9: *Preliminary results from the SSEM Pilot Project: long-term mean biases on LAGEOS and LAGEOS-2 for the period 1993–2019, from a simultaneous estimation of weekly positions and biases for all systems. Note that the majority of the Core stations demonstrate a more random distribution in a $\pm$5 mm bracket, half of what it was using the older modeling approach.*

particular workshops in Kunming, PRC (2020) and Arequipa, Peru (2021) were postponed to 2021 and 2022 respectively.

Publications

In 2019 the ILRS completed and published the 2nd Special Issue on Laser Ranging in the Journal of Geodesy, Vol. 93, 11, comprising of 287 pages, with twenty articles and a preface. An extensive list of general publications of interest to ILRS associates can be found at the ILRS website:

https://ilrs.gsfc.nasa.gov/about/reports/biblio/bibliography.2019.html

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