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 2018.

Network

The network of SLR/LLR stations (Figure 1), under the aegis of the ILRS, has been subject to change over the years. In 2018 the network remained very much in its past years form. The only significant change was the introduction of a new system (laser) at the old Kunming 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 2018 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 about 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.

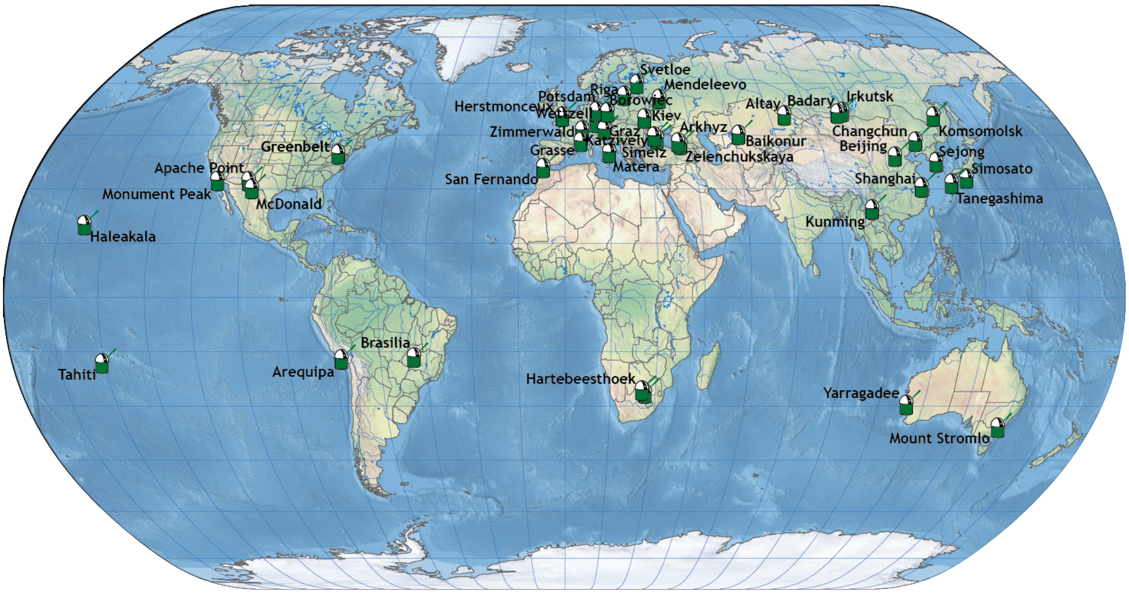

Fig. 1: *The global network of SLR stations (status late 2018).*

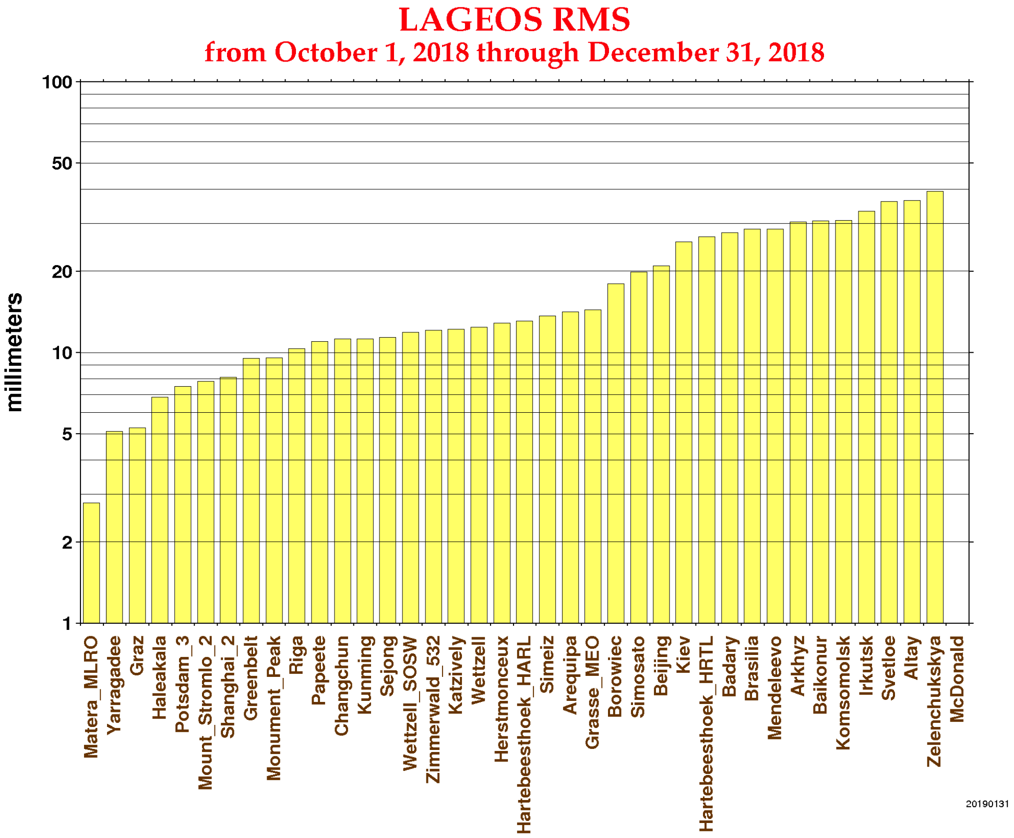

Fig. 2: *: Performance of the global network of SLR stations on LAGEOS (last quarter of 2018).*

Table 1: *ILRS Network Tracking Statistics for 2018*

		NUMBER OF PASS SEGMENTS			
SITE NAME	**Station**	**LEO**	**MEO**	**HEO**	**Total**
ALTAY	1879	74	319	2,012	2,405
AREQUIPA	7403	3,521	233	0	3,754
ARKHYZ	1886	441	247	697	1,385
BADARY	1890	1,235	331	203	1,769
BAIKONUR	1887	3	336	1,118	1,457
BEIJING	7249	1,902	481	1,449	3,832
BOROWIEC	7811	966	314	70	1,350
BRASILIA	7407	325	358	790	1,473
CHANGCHUN	7237	9,488	1,434	5,255	16,177
GRASSE	7845	45	236	864	1,145
GRAZ	7839	3,734	817	2,488	7,039
GREENBELT	7105	6,552	1,392	1,106	9,050
HALEAKALA	7119	1,643	478	0	2,121
HARTEBEESTHOEK	7501	3,729	1,174	1,814	6,717
HARTEBEESTHOEK	7503	1,096	315	453	1,864
HERSTMONCEUX	7840	5,841	1,393	4,643	11,877
IRKUTSK	1891	1,393	478	842	2,713
KATZIVELY	1893	1,928	318	9	2,255
KIEV	1824	571	87	0	658
KOMSOMOLSK	1868	39	248	1,917	2,204
KUNMING	7819	2,635	594	3,049	6,278
MATERA	7941	4,320	1,955	3,336	9,611
MCDONALD	7080	137	29	2	168
MENDELEEVO	1874	107	113	295	515
MONUMENT PEAK	7110	7,340	938	852	9,130
MOUNT STROMLO	7825	6,702	1,747	2,479	10,928
POTSDAM	7841	4,783	1,094	1,149	7,026
RIGA	1884	1,047	175	35	1,257
SEJONG	7394	397	122	9	528
SHANGHAI	7821	2,742	818	3,073	6,633
SIMEIZ	1873	2,182	467	397	3,046
SIMOSATO	7838	1,150	436	19	1,605
SVETLOE	1888	681	184	109	974
TAHITI	7124	1,246	263	590	2,099
WETTZELL	7827	2,522	832	3,444	6,798
WETTZELL	8834	4,812	1,159	4,012	9,983
YARRAGADEE	7090	26,270	5,500	13,053	44,823
ZELENCHUKSKAYA	1889	825	209	364	1,398
ZIMMERWALD	7810	8,046	1,860	4,594	14,500
GRAND TOTALS:	39 stations	122,470	29,484	66,591	218,545

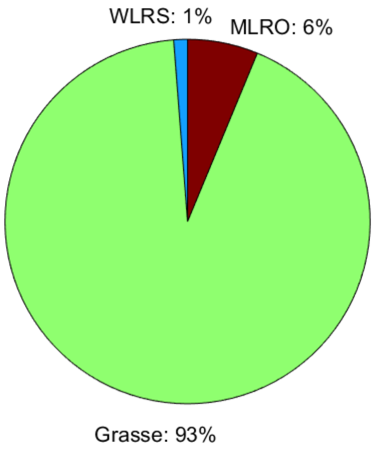

Fig. 3: *Observatory statistics in 2018 (except for APOLLO, not available yet).*

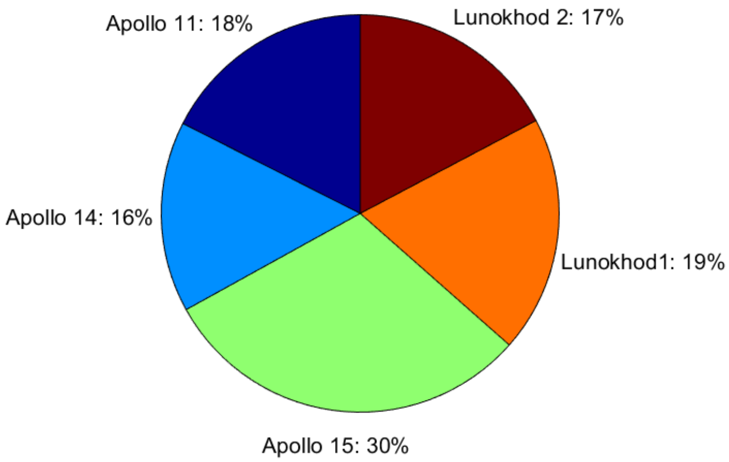

Fig. 4: *Retro-reflector statistics by reflector in 2018.*

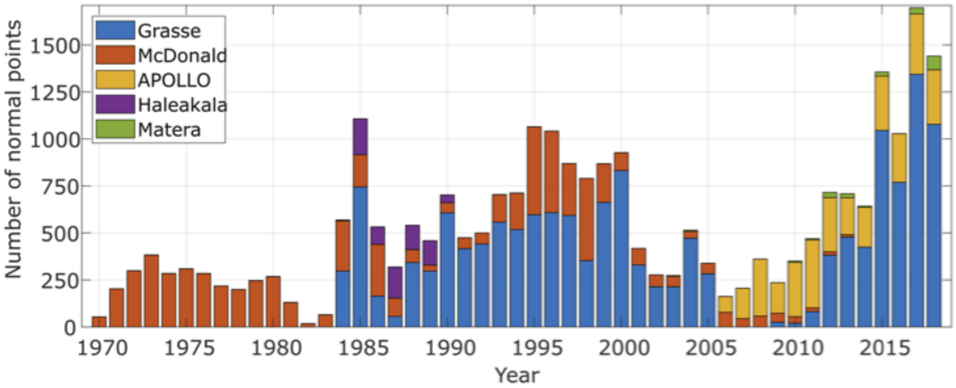

Fig. 5: *Data yield of the global LLR network of stations (up to end of 2018). Note the increased contribution of Grasse's MeO system upon its return to operations in 2011, the steady yield of APOLLO, the small increase at Matera, and the absence of McDonald Obs. the last five years.*

Statistics of the SLR data collected as pass segments during the calendar year 2018 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 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

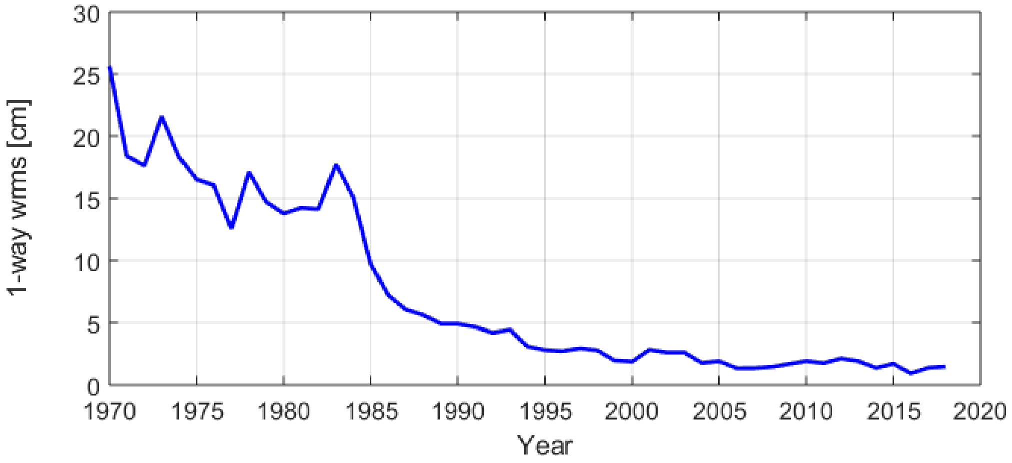

Fig. 6: *LLR residuals, annual WRMS 1970 to 2018.*

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

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

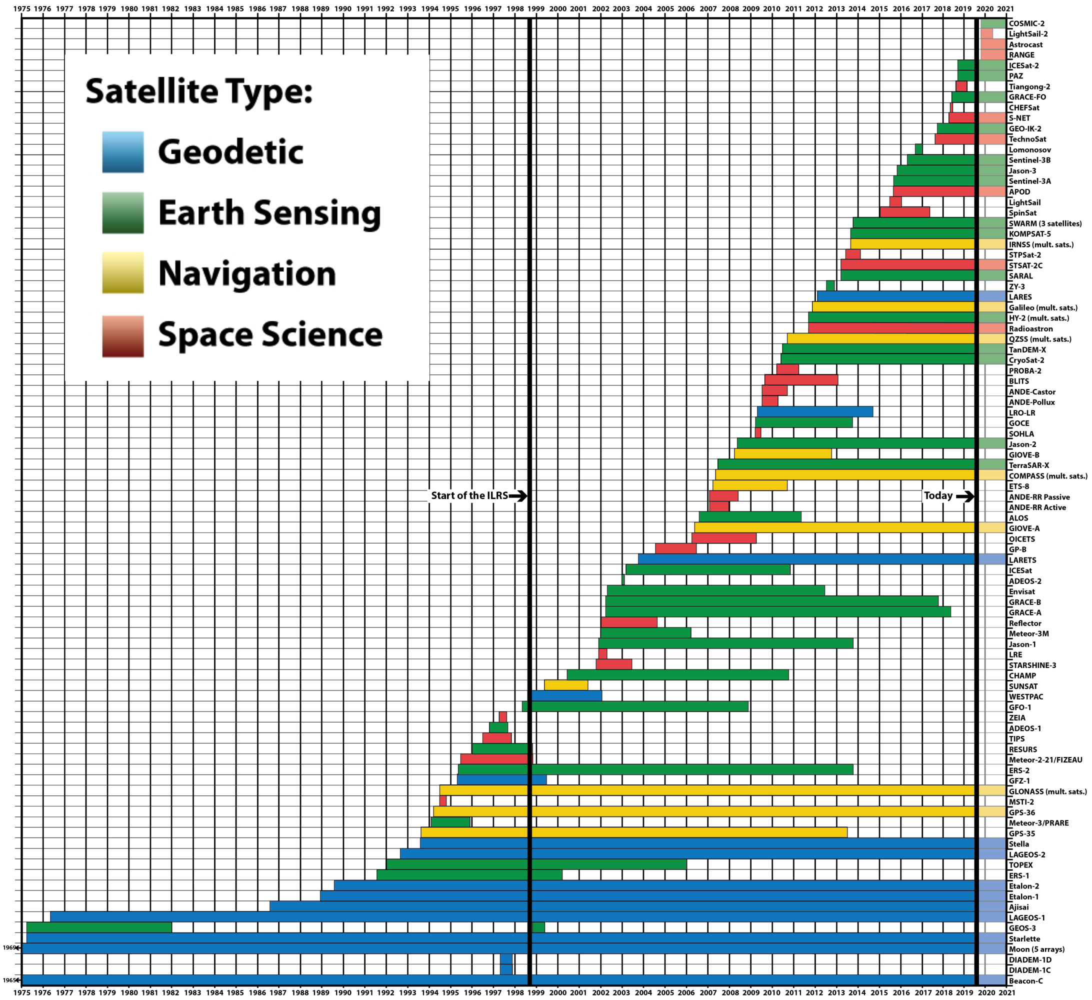

Fig. 7: *The currently tracked SLR missions (status as of early 2019).*

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 study 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 2018, a total of ~120 targets, including those on the moon, were being tracked by SLR/LLR (Figure 7). This indicates a ~20% increase in targets since 2017. 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 2018 the steady increase of tracking multiple GNSS targets continued for a seventh year in a row. The three tracking campaigns initiated in 2017 for the three QZS spacecraft were completed by February 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. The launch of the GRACE Follow-On mission resulted in the initiation of a tracking campaign in late 2018, which will be finalized in 2019:

- *August 25, 2017–February 28, 2018 – QZS-2 tracking campaign*
- *November 01, 2017–February 28, 2018 – QZS-3 tracking campaign*
- *December 01, 2017–February 28, 2018 – QZS-4 tracking campaign*
- February 15–May 15 – First LARGE campaign of 2018
- August 01–October 31 – Second LARGE campaign of 2018
- December 15, 2018–January 15, 2019 – GRACE-FO tracking campaign

The seventeen new missions that were launched during 2018 are shown in Table 2. Seven spacecraft were part of GNSS Constellations, six were remote sensing and Earth observation missions and four comprised a small experimental constellation of CubeSats. Despite the significant increase in the number of targets in 2018, the ILRS network has increased its productivity to keep pace with this increased demand for support, and kept the data yield rate positive, as in the past years (Figure 8).

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 (Â°)	First Date Tracked
GLONASS-139	1808601	9139	43687	9	300	19,140	65	2018-Nov-03
HY-2B	1808101	2208	43655	5	30	971	99.35	2018-Nov-01
ICESat-2	1807001	6873	43613	1	5	496	92	2018-Nov-02
Galileo-220	1806004	7220	43567	9	300	23,220	56 ± 2 deg	2018-Oct-17
Galileo-219	1806003	7219	43566	9	300	23,220	56 ± 2 deg	2018-Oct-17
GRACE-FO-2	1804702	124	43477	1	5	500	89	2018-May-23
GRACE-FO-1	1804701	123	43476	1	5	500	89	2018-May-23
Sentinel-3B	1803901	8011	43437	3	15	814.5	98.65	2018-May-03
IRNSS-1I	1803501	3309	43286	9	300	35,786	5	2018-May-09
BeiDou-3M10	1802902	2020	43246	9	300	21,500	55	2018-Aug-03
BeiDou-3M9	1802901	2019	43245	9	300	21,500	55	2018-Aug-04
PAZ	1802001	2501	43215	1	5	514	97.44	2018-Feb-22
BeiDou-3M3	1801802	2015	43208	9	300	21,500	55	2018-Aug-10
SNET-1	1801410	6204	43189	1	5	600	97.6 - 97.9 deg	2018-Apr-27
SNET-4	1801409	6207	43188	1	5	600	97.6 - 97.9 deg	2018-Apr-12
SNET-3	1801408	6206	43187	1	5	600	97.6 - 97.9 deg	2018-Apr-20
SNET-2	1801407	6205	43186	1	5	600	97.6 - 97.9 deg	2018-Apr-21

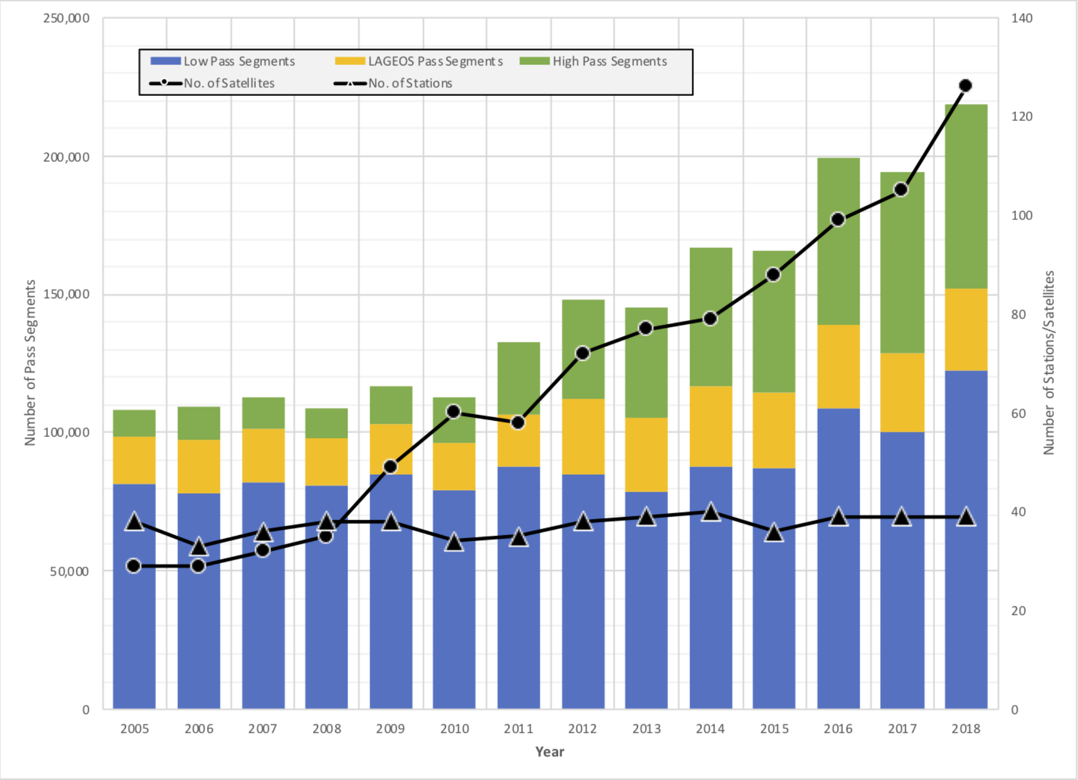

Fig. 8: *ILRS network data yield by target type since 2005 and up to the end of 2018.*

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. A re-analysis of the main ILRS targets LAGEOS and LAGEOS-2 was completed and in 2018 it included the two Etalons, since it became obvious that these targets were not modeled sufficiently accurately. The re-analysis revealed serious shortcomings of the "target signature" model (aka "center of mass" – CoM correction), so a new model was developed, leading to significant changes over the previous model. A second reanalysis followed the first, this time using the corrected CoM model, delivering preliminary results for the expected changes in the ITRF scale realized by the SLR technique. These preliminary results are very promising because they indicate that the new SLR-implied scale is significantly closer to that implied by VLBI, bringing the gap down by more than 1 ppb! When the re-analysis is completed the new approach will transition to a fully operational product that will become available in 2019, once a trial period with the participation of all ILRS ACs is successfully completed. The weekly scale estimates from a preliminary combination were compared to the original results using the old approach (no simultaneous bias estimation) over 1993 to 2018 period to get an estimate of what is to be expected for the ITRF2020 re-analysis (Figure 9).

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 will be completed in 2018, and the operational service will be in test mode during early 2019.

Meetings

In 2018 the ILRS held the 21st International Workshop on Laser Ranging, in Canberra, Australia, November 04–08, followed by a 1-day Workshop on Space Debris. The theme for the main workshop was: "Laser Ranging for Sustainable Millimeter Geoscience" and the topics that were addressed:

- SLR Contribution to Global Geodetic Observing System – A 2020 Perspective
- Improvements in the SLR Product Quality and Precise Orbit Determination
- Satellite Missions and Techniques for Geodetic Applications
- Characteristics of Retroreflector Arrays

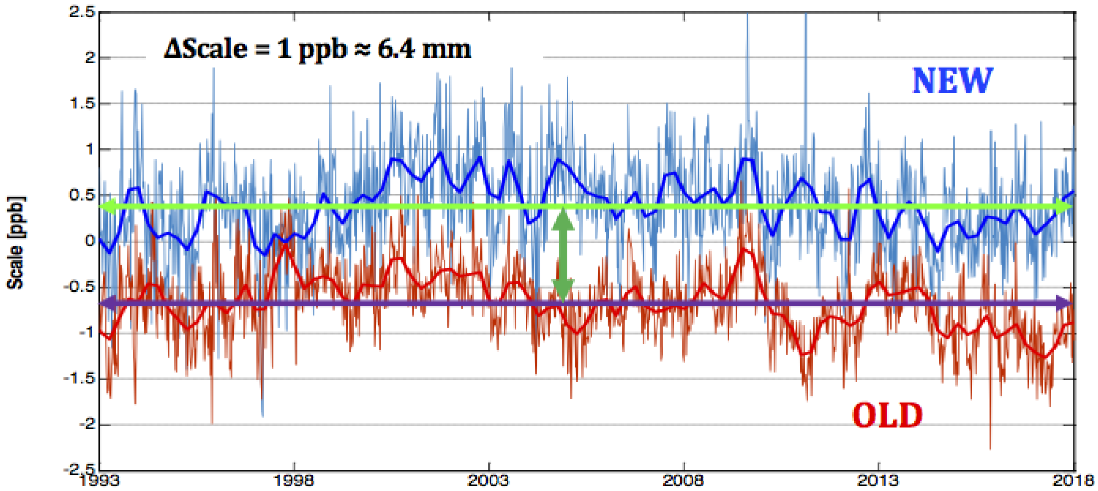

Fig. 9: *Preliminary results from the SSEM Pilot Project: comparison of the SLR scale realized in the standard weekly series (OLD) and the newly adopted approach (NEW). The horizontal lines are roughly at the average values of the two series over the period 1993–2018 (∼1305 weeks), to provide a figure of merit for the expected scale change in the ITRF2020 development.*

- Sources of Systematic Errors
- Network Operations and Site Upgrades
- Developments in SLR Techniques and Technologies
- Developments in Software and Automation
- Lunar Laser Ranging and Deep Space Missions

The workshop was very well attended with over 150 participants from many countries, nearly 80 oral presentations and 60 poster presentations. An additional 25 oral and 15 poster presentations were presented during the Workshop on Space Debris. The ASC held two meetings in 2018, one during the EGU General Assembly, on April 12, and one prior to the Canberra Workshop, on November 1. The ILRS Governing Board met once in 2018, prior and at the conclusion of the Canberra workshop on November 4 and 8. In 2019 the ILRS will hold a Technical Workshop on Laser Ranging that will take place in Stuttgart, Germany, October 21–25. For more information please see:

https://ilrsworkshop2019.besl-eventservice.de

The topic of the 2019 Technical Workshop is: “Laser ranging: To improve economy, performance, and adoption for new applications”.

Publications

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

https://ilrs.cddis.eosdis.nasa.gov/about/reports/biblio/bibliography.2018.html

References

Courde C, Torre JM, Samain E, Martinot-Lagarde G, Aimar M, Albanese D, Exertier P, Fienga A, Mariey H, Metris G, Viot H, Viswanathan V *(2017) Lunar laser ranging in infrared at the Grasse laser station. Astron. Astrophys. 602:A90, DOI 10.1051/0004-6361/201628590*

Hofmann F, Müller J *(2018) Relativistic tests with Lunar Laser Ranging. Class. Quantum Grav. 35:035015, DOI 10.1088/1361-6382/aa8f7a*

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

Williams JG, Boggs DH *(2016) Secular tidal changes in lunar orbit and Earth rotation. Celest. Mech. Dyn. Astron. 126:89–129, DOI 10.1007/s10569-016-9702-3*

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