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 2016.

Network

The network of SLR/LLR stations (Figure 1), under the aegis of the ILRS, has been subject to change over the years. In 2016 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 a few stations doing significantly better. Nearly all stations deliver normal points 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. Examination of the tracking over the past year indicates that the tracking of targets increased by 10%, with a similar increase in the number of tracking sites, with the combined effect resulting in a 20% increase of the annual data yield of the network (Table 1 and Figure 7). 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. 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. All sites will be co-located with GNSS systems primarily intended to tie the GLONASS monitoring network with that of the SLR. This addition will eventually improve tremendously the tie between the SLR-, GNSS-, and VLBI-implied frames.

Table 1: *ILRS Network Tracking Statistics for 2016*

Site Name	Station	Number of Pass Segments			
		Low	LAGEOS	High	Grand Total
Altay	1879	142	383	2,224	2,749
Apache Point	7045	0	0	259	259
Arequipa	7403	2,844	275	0	3,119
Arkhyz	1886	402	346	1,000	1,748
Badary	1890	1,563	230	77	1,870
Baikonur	1887	37	274	902	1,213
Beijing	7249	703	225	469	1,397
Borowiec	7811	443	230	18	691
Brasilia	7407	398	472	1,299	2,169
Changchun	7237	10,743	2,371	8,820	21,934
Grasse	7845	1,114	638	835	2,587
Graz	7839	3,539	957	3,089	7,585
Greenbelt	7105	5,961	1,629	1,377	8,967
Haleakala	7119	2,212	734	0	2,946
Hartebeesthoek	7501	1,204	411	129	1,744
Herstmonceux	7840	8,684	2,546	7,561	18,791
Irkutsk	1891	697	396	568	1,661
Katzively	1893	1,423	416	61	1,900
Kiev	1824	474	76	0	550
Komsomolsk	1868	69	341	2,165	2,575
Matera	7941	1,611	1,050	1,785	4,446
McDonald	7080	323	42	15	380
Mendeleevo	1874	127	136	244	507
Monument Peak	7110	6,328	900	1,112	8,340
Mount Stromlo	7825	12,555	3,392	5,186	21,133
Potsdam	7841	5,722	1,441	788	7,951
Riga	1884	493	212	59	764
San Fernando	7824	104	4	2	110
Sejong	7394	879	279	115	1,273
Shanghai	7821	1,926	523	2,126	4,575
Simeiz	1873	1,205	367	91	1,663
Simosato	7838	945	407	24	1,376
Svetloe	1888	996	389	107	1,492
Tahiti	7124	919	291	613	1,823
Wettzell	7827	3,254	1,452	4,526	9,232
Wettzell	8834	2,912	702	2,635	6,249
Yarragadee	7090	20,757	4,321	8,544	33,622
Zelenchukskaya	1889	595	300	291	1,186
Zimmerwald	7810	4,542	1,249	680	6,471
Totals:	39 stations	108,845	30,407	59,796	199,048

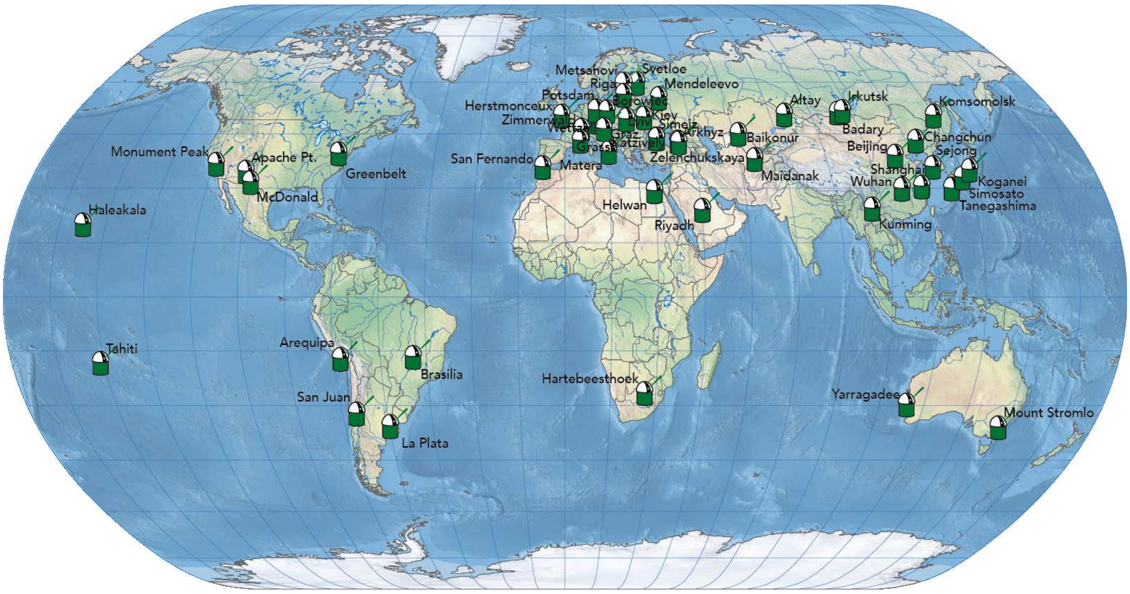

Fig. 1: *The global network of SLR stations (status early 2017).*

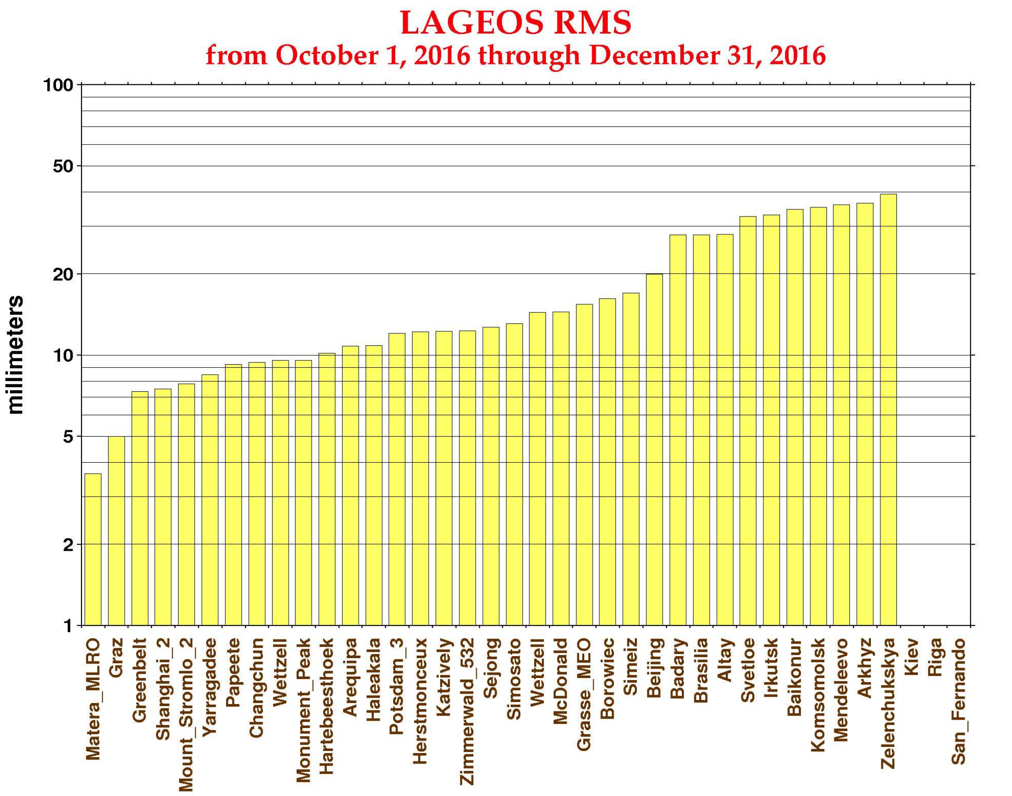

Fig. 2: *Performance of the global network of SLR stations on LAGEOS (last quarter of 2016).*

Statistics of the SLR data collected as pass segments during the calendar year 2016 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, GIOVE-A/B, Galileo, BeiDou, IRNSS and the Moon.

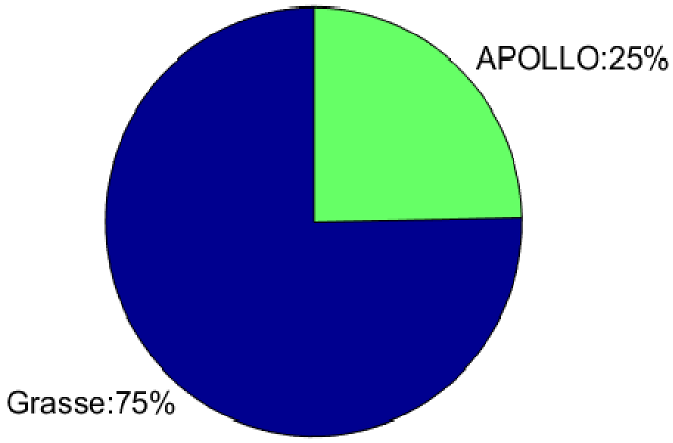

Fig. 3: *Observatory statistics in 2016.*

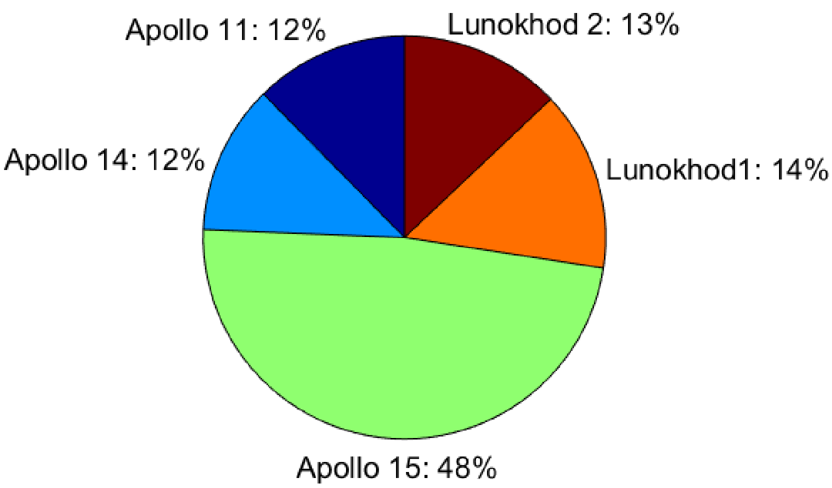

Fig. 4: *Retro-reflector statistics in 2016.*

Currently there are only four Lunar Laser Ranging (LLR) capable stations within the ILRS network of about 39 laser ranging stations. These LLR stations are also SLR capable (except for APOLLO located in New Mexico, USA) in addition to being technically equipped to track the retro-reflector arrays placed on the surface of the Moon or retro-reflector equipped spacecraft orbiting the Moon. The other three LLR capable stations 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 McDonald Laser Ranging Station (MLRS) in Texas, USA. During 2016, LLR data from only one of these four sites (MeO, 52 normal points (NP)) were uploaded to the Crustal Dynamics Data Information System (CDDIS) although APOLLO data were also available. The quantity of data for 2016 was slightly less in comparison to 2015. In 2015 MLRS returned to service after one year without any lunar measurements, contributing only two successful lunar tracks, but without any contributions during 2016. Since the latter part of 2014 the Grasse LLR system MeO has ranged at infrared wavelength (1064 nm), and these data are available at their website (http://www.geoazur.fr) and included in the statistics shown in Figures 3 to 5. Most of the MeO LLR data are now obtained with infrared instead of green wavelength (532 nm) laser pulses.

Further development of LLR capabilities at McDonald in the future depends on decisions to be made following the establishment of a new generation SLR system at McDonald, through NASA's Space Geodesy Project-SGP, the SGSLR. The support for the LLR component is unclear at this time, but it is likely to be discontinued. This discontinuation will be a disappointment as the McDonald station has been a major contributor to LLR data over a long period of time.

The measurement statistics of 2016 (Figure 3) indicate that 75% of all LLR data have been collected at the French MeO site near Grasse and 25% at APOLLO. Figure 4 illustrates the statistics for the observed retro-reflectors, nearly half the data (48%) were obtained from the Apollo 11 reflector array, with the balance made up, nearly equally, by the other four reflector arrays. Figure 5 reflects the entire LLR data set from 1970 to 2016 indicating the amount of data collected by each of the active LLR sites in each year. There are more than 22,000 normal points in total. After several years of low data production with fewer LLR normal points, the last two years (2015, 2016) indicated a higher productivity, although the active number of stations declined. These numbers do not contain quite new measurements carried out in infra-red at the French site. Data from the APOLLO station was last released to CDDIS in 2014, which means that all data are not yet available in the archive.

LLR data analysis is carried out at 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; and 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. Some interest towards this end have also been shown by the Hartebeesthoek Radio Astronomy Observatory (HRAO), South Africa, where an ex-Observatoire de la Côte d'Azur 1-m aperture telescope is being prepared for LLR use.

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 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.

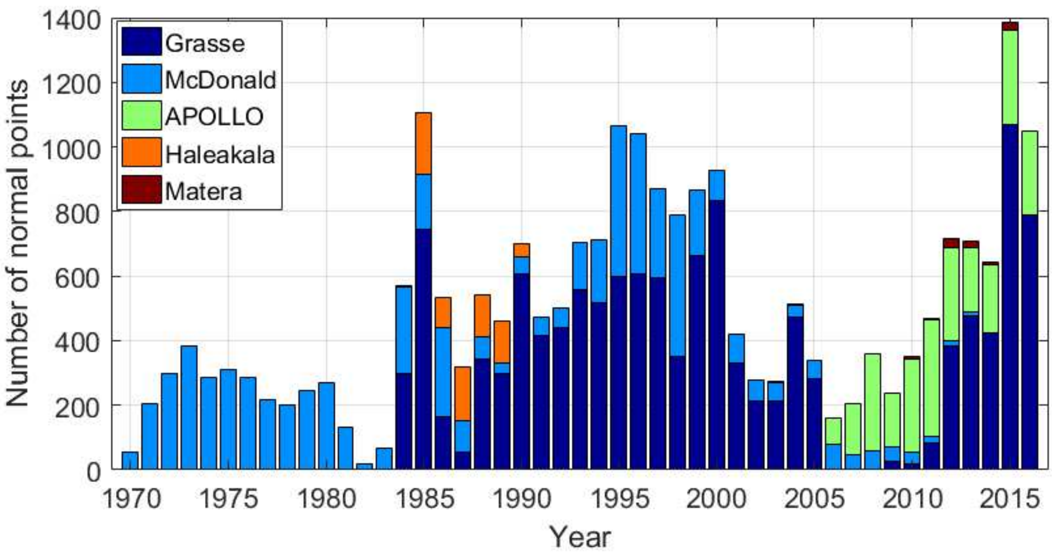

Fig. 5: *Data yield of the global LLR network of stations (up to 2016). Note the increasingly significant contribution of Grasse' s MeO system upon its return to operations in 2011.*

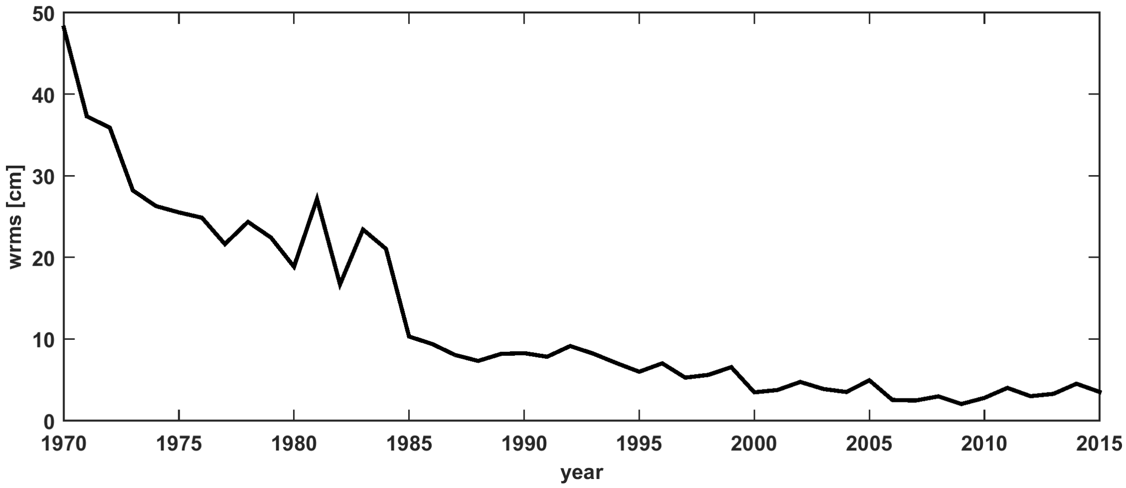

Fig. 6: *LLR residuals, annual WRMS.*

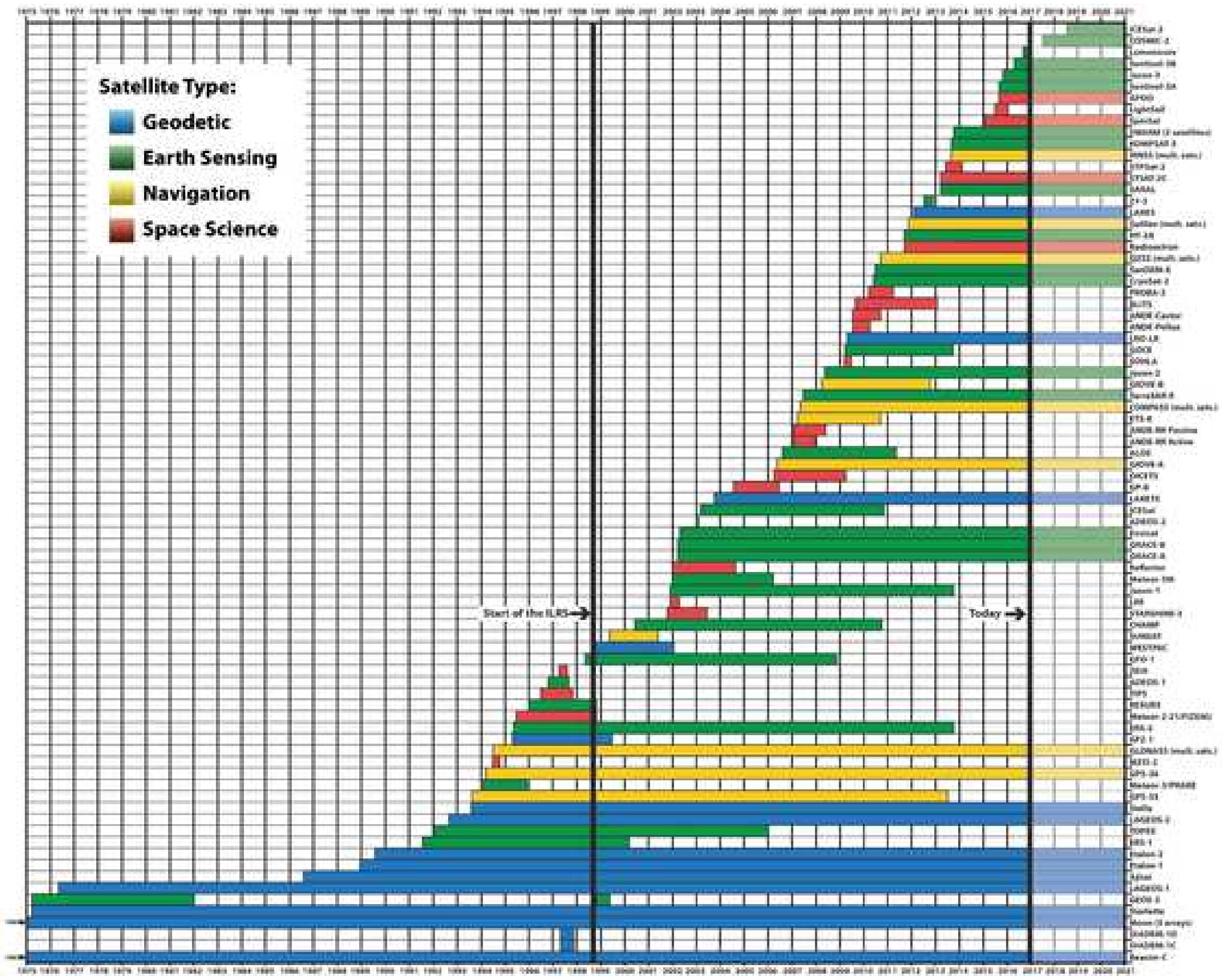

Fig. 7: *The currently tracked SLR missions (status as of late 2016).*

Missions In 2015, a total of 38 missions including the Moon (over 70 targets!) were being tracked by SLR/LLR (Figure 7). Of these, only about 1/3 are geodetic type targets (cannonball satellites), about one half are navigation satellites and the rest are mainly Earth Observation missions, along with a small number of experimental space science missions. In 2015 the steady increase of tracking multiple GNSS targets continued for a fifth 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 further increase in data yield from such missions.

Table 2: *ILRS Supported Missions Launched or Initiating Tracking in 2016*

Satellite Name	Satellite ID	SIC Code	Satellite Catalog Number	NP Indicator	Bin Size (sec)	Altitude (Km)	Inclination (°)	First Data Date
Galileo-212	1606902	7212	41860	9	300	23,220	56 ± 2	2017-Feb-20
Galileo-213	1606903	7213	41861	9	300	23,220	56 ± 2	2017-Feb-20
Galileo-214	1606904	7214	41862	9	300	23,220	56 ± 2	2017-Feb-20
Galileo-207	1606901	7207	41859	9	300	23,220	56 ± 2	2017-Feb-16
GLONASS-136	1603201	9136	41554	9	300	19,140	65	2016-May-29
IRNSS-1F	1601501	3306	41384	9	300	35,786	5	2016-May-26
COMPASS-I6B	1602101	2012	41434	9	300	35,677	55.5	2016-Mar-29
Galileo-210	1603002	7210	41550	9	300	23,220	56 ± 2	2016-Jun-12
Galileo-211	1603001	7211	41549	9	300	23,220	56 ± 2	2016-Jun-12
Jason-3	1600201	4379	41240	3	15	1336	66	2016-Jan-20
IRNSS-1E	1600301	3305	41241	9	300	35,786	29	2016-Jan-20
Sentinel-3A	1601101	8010	41335	3	15	814.5	98.65	2016-Apr-01

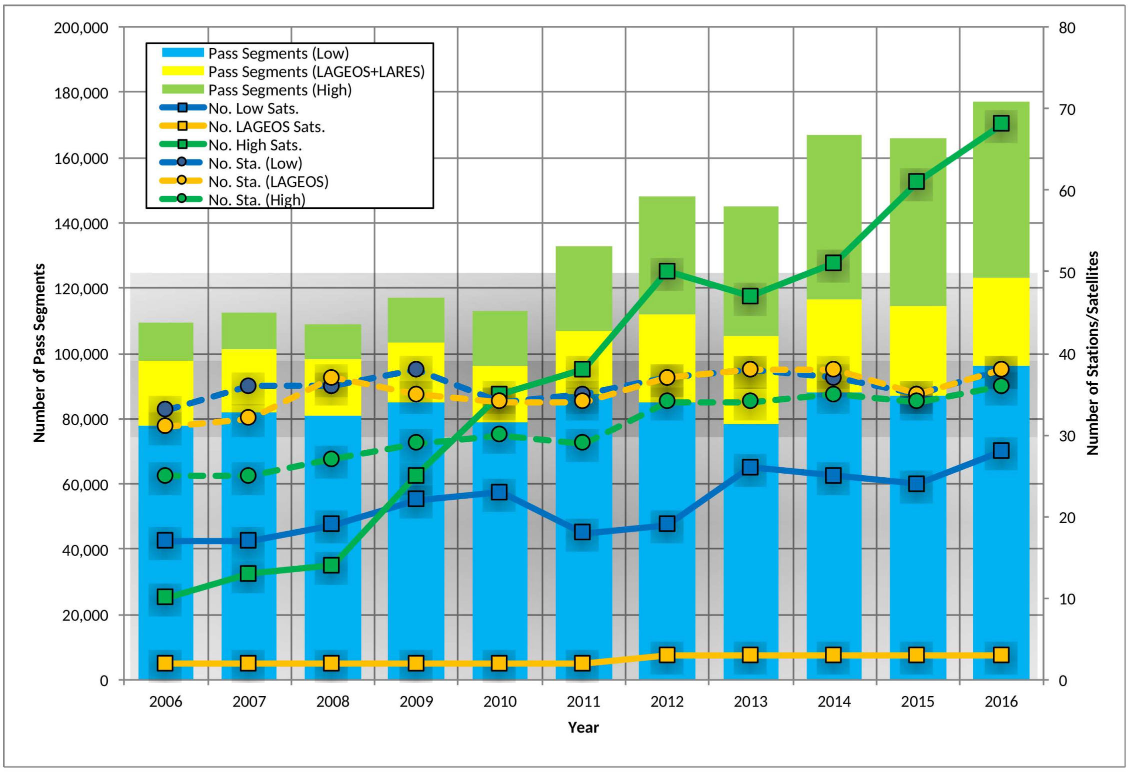

Fig. 8: *ILRS network data yield by target type since 2006 (by end of 2016).*

During 2016 the new missions that were launched are shown in Table 2. They were mostly spacecraft of GNSS Constellations. Notably though, we also had the launch of the new oceanographic mission Jason-3 and that of ESA' s Sentinel-3A mission.

Despite the increase in the number of targets in 2016, the ILRS network has increased its productivity tremendously (by 20%) for an improved data yield this past year (Figure 8). A major contributor in the recent years' data yield increase is the fact that several stations upgrade their capability to track all GNSS satellites whose numbers are steadily increasing these past 3–4 years.

Analysis and science

The Analysis Standing Committee (ASC) based on the final version of the ITRF2014 developed SLRF2014 to include additional ILRS sites that were not part of the official ITRF2014 release or came online after its completion. The expanded TRF model will become the new official ILRS model once the validation of the contributions from all ACs is completed, sometime in early 2017.

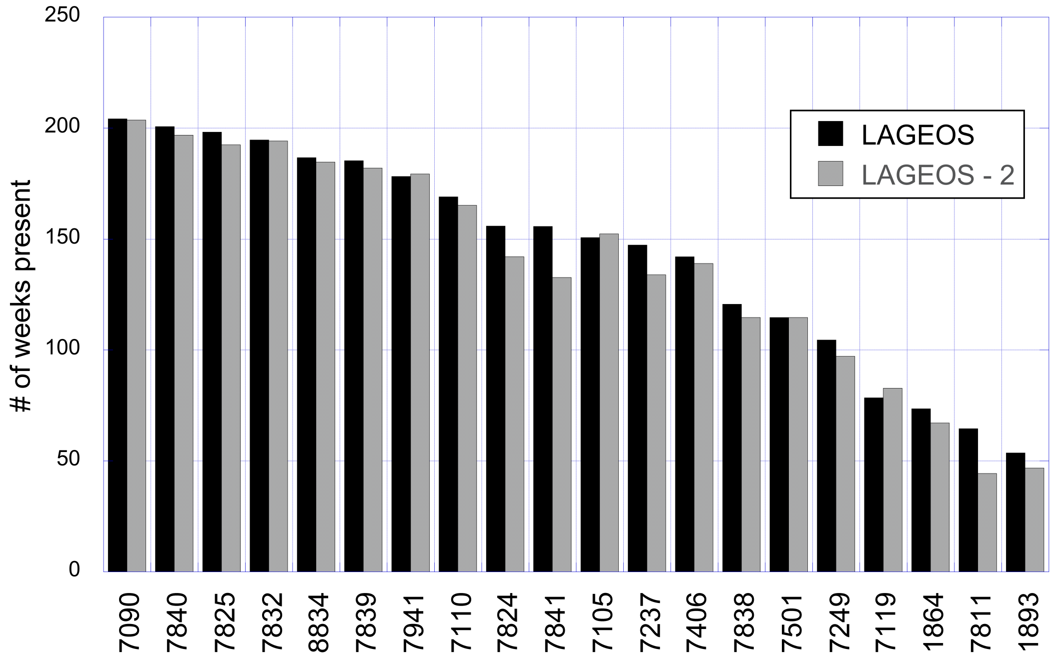

Fig. 9: *The number of weeks that ILRS stations contributed to the SSEM Pilot Project over the period 2005–2008 (out of a maximum of 208 weeks). Stations averaging less than 50 weeks per target are not shown.*

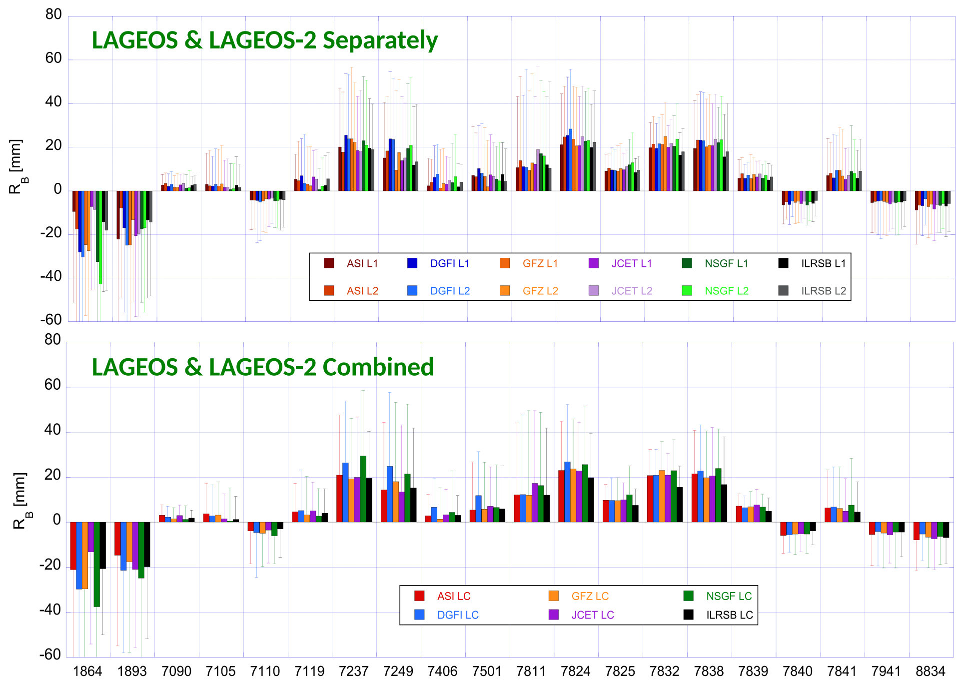

Fig. 10: *The averaged systematics for twenty ILRS stations, for each target separately (top) and in combination (bottom), based on the Station Systematic Error Monitoring Pilot Project results (averaged over the period 2005–2008).*

The effort to identify, mitigate and monitor systematic errors in the ILRS data has continued over the past year with many new initiatives. The Pilot Project to develop a strategy for a combined product that delivers estimates of station systematics on a regular basis was executed with success, with the participation of most of the ILRS ACs. The results indicated the best practice would be to monitor separately the systematics on each of the main ILRS targets (LAGEOS and LAGEOS-2, eventually including LARES), and to allow for long-term averaging of the results of weekly estimates. This is now being transitioned to an operational product, which will become available in 2017, once a trial period with the participation of all ILRS ACs is successfully completed. The pilot project was restricted to the time-period 2005–2008, delivering estimates of the systematic errors of the entire network while simultaneously allowing the estimation of the stations' coordinates. The results are therefore by and large independent of the underlying TRF or any errors it may inherently possess. The selected period comprised a robust set of data for most of the stations (Figure 9). The weekly estimates were averaged over the 4-year period to obtain more reliable mean estimates for each target separately as well as a combined estimate for both, LAGEOS and LAGEOS-2. These averaged results are displayed in Figure 10 for the twenty most prolific stations over that period.

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_v200+v210/configuration.php

A sample page with the comparison of several AC results for LAGEOS and throughout the test period 2005–2008 is displayed in Figure 11. Note that the results are all very close to each other, indicating the high degree of consistency between ACs' analysis, and to the combined estimate indicated by the black dashed line.

The next step 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 need to develop a long history of systematics for each station separately. This is a task to be completed in 2017, after the adoption of the new SLRF2014 model by all participating ACs.

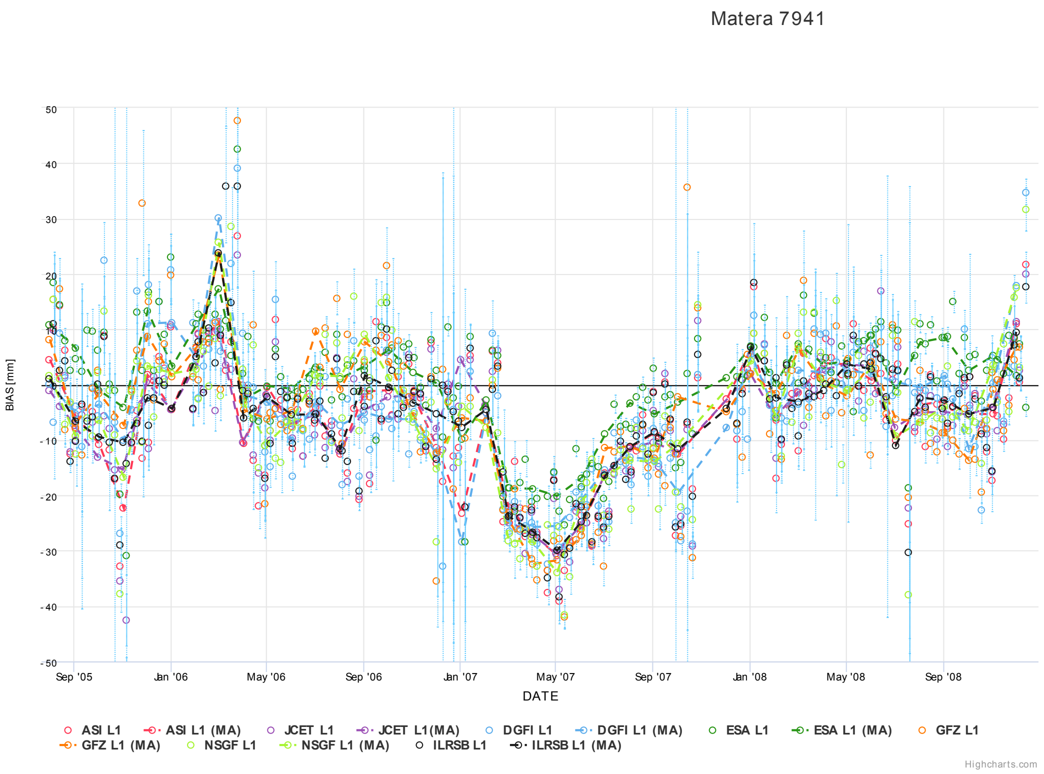

Fig. 11: *Weekly estimates of the systematic error for the Matera, Italy MLRO system (7941). The circles indicate the weekly results while the dashed lines a "moving average" estimate (MA). The black color results are the combination of the individual AC contributions.*

Meetings

In 2016 the 20th International Laser Workshop was held at GFZ Potsdam, Germany, during the week of October 9–14, co-sponsored by the Helmholz Center Potsdam – GFZ German Research Centre for Geosciences and the ILRS. The theme for this workshop was: "The Path

Toward the Next Generation Laser Ranging Network" and the topics that were addressed:

- Advances in laser ranging technology and new applications;
- Co-locations and other intra- and inter-technique calibrations;
- Strategies and priorities for laser ranging;
- Understanding and addressing SLR station systematics;
- Progress in laser ranging analysis;
- Current trends in lunar ranging;
- SLR tracking of space debris;
- Automation of laser ranging systems;
- Interplanetary ranging and time transfer; and
- Advances in retroreflector arrays and their modeling.

The workshop was very well attended with over 170 participants from 25 countries, 80 oral presentations and over 60 posters. The ASC held two meetings in 2016, one during the EGU General Assembly, on April 22, and one prior to the Potsdam Workshop, on October 8. The ILRS Governing Board met once in 2016, prior to the Potsdam workshop on October 8. The ILRS will hold in 2017 an ILRS Technical Workshop that will take place in Riga, Latvia, co-hosted by Institute of Astronomy at the University of Latvia, October 2–5. For more information see:

http://www.ilrstw2017.lu.lv

The topic of the 2017 Workshop is: "Improving ILRS Performance to Meet Future GGOS Requirements".

Publications

Access all the presentations, posters, and proceedings papers presented at the 20th International Laser Workshop at GFZ Potsdam, Germany from the official ILRS page for the workshop:

https://cddis.nasa.gov/lw20/Program/

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.2016.html

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