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 2014. This year is a very special one for SLR because it marks the 50th year anniversary since the first successful tracking of a satellite target, on October 31, 1964, from a NASA Goddard tracking system deployed at what is today known as the Goddard Geophysical and Astronomical Observatory (GGAO), in Greenbelt, Maryland. The ILRS celebrated this historical event by organizing the 19th International Laser Workshop at Annapolis, Maryland over October 26–31, 2014, including a one-day visit of the Goddard campus and a tour of the GGAO facilities. The workshop's complete program including all presentations, posters and online proceedings can be found at <http://cddis.gsfc.nasa.gov/lw19/index.html>.

Network

The network of SLR/LLR stations (Figure 1), under the aegis of the ILRS, has been subject to change over the years. In 2014 the network expanded with the addition of several new sites, most of them deployed by Russia, in support of their GLONASS tracking network. Most of the new sites are filling gaps that were void of SLR stations for many decades (e.g. Brasilia, Brazil, Irkutsk, Russia, etc.). From a technical perspective, the quality

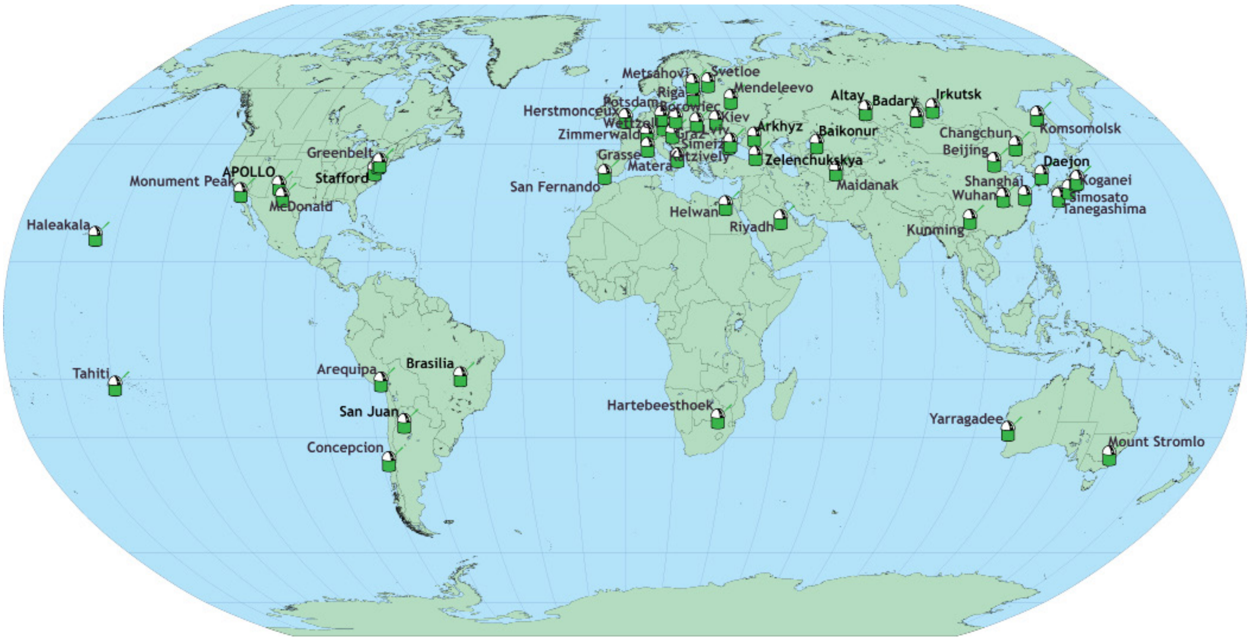

Fig. 1: The global network of SLR stations (status early 2015).

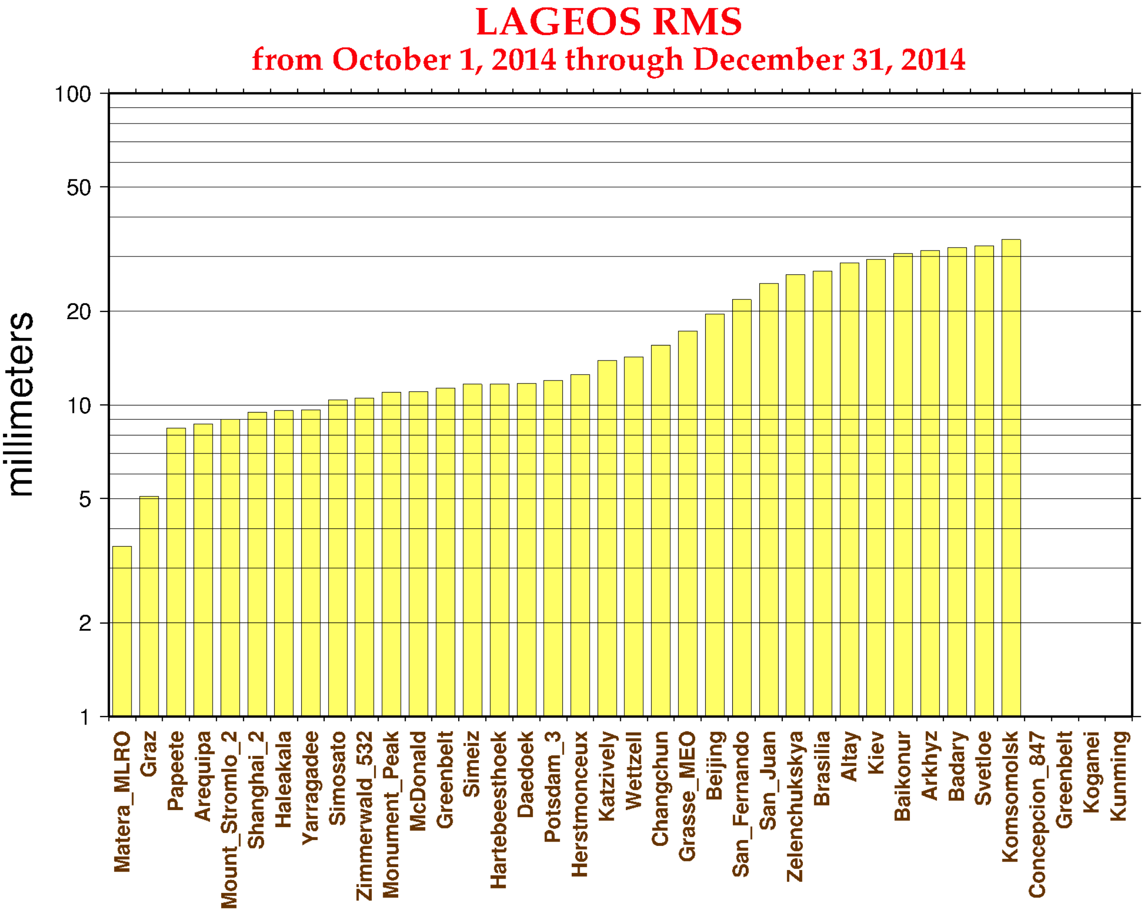

Fig. 2: Performance of the global network of SLR stations on LAGEOS (last quarter of 2014).

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 at the 10 mm level, with a significant number of 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. This allowed the modification of the Normal Point (NP) forming recipe to improve the efficiency and data yield of the network, limiting the tracking to the minimum number of single shots required to reach the 1 mm NP precision. Examination of the tracking over the past year indicates that the tracking of targets increased without loss of data accuracy or other impact on the computed orbital products. NASA is moving forward to begin the production of next generation Space Geodesy SLR systems (SGSLRs) that will replace the current network and fill

Table 1: ILRS Network Tracking Statistics for 2014.

		Number of Passes			
Site Name	**Station**	**Low**	**LAGEOS**	**High**	**Total**
Altay	1879	161	241	1,733	2,135
Arequipa	7403	2,848	501	0	3,349
Arkhyz	1886	478	321	1,016	1,815
Badary	1890	1,763	489	353	2,605
Baikonur	1887	26	396	587	1,009
Beijing	7249	925	257	556	1,738
Brasilia	7407	0	115	239	354
Changchun	7237	9,602	2,403	7,192	19,197
Concepcion	7405	115	62	3	180
Daejon	7359	983	257	393	1,633
Grasse	7845	525	468	1,273	2,266
Graz	7839	3,233	974	2,807	7,014
Greenbelt	7105	4,908	1,438	1,390	7,736
Greenbelt	7125	36	45	28	109
Haleakala	7119	1,389	564	0	1,953
Hartebeesthoek	7501	2,675	1,456	1,133	5,264
Herstmonceux	7840	3,010	1,128	2,429	6,567
Katzively	1893	1,431	273	10	1,714
Kiev	1824	1,349	326	11	1,686
Koganei	7308	73	34	76	183
Komsomolsk	1868	34	111	1,110	1,255
Kunming	7820	783	167	0	950
Matera	7941	2,569	1,634	2,588	6,791
McDonald	7080	1,015	467	439	1,921
MonumentPeak	7110	4,779	1,244	1,170	7,193
MountStromlo	7825	6,902	2,091	3,311	12,304
Potsdam	7841	2,407	550	233	3,190
SanFernando	7824	299	48	0	347
SanJuan	7406	2,149	955	711	3,815
Shanghai	7821	1,725	505	1,496	3,726
Simeiz	1873	729	243	95	1,067
Simosato	7838	1,002	374	80	1,456
Svetloe	1888	1,158	943	474	2,575
Tahiti	7124	557	223	418	1,198
Wettzell	8834	3,945	1,217	3,527	8,689
Yarragadee	7090	16,792	4,304	8,064	29,160
Zelenchukskaya	1889	440	278	897	1,615
Zimmerwald	7810	5,027	1,738	3,916	10,681
Totals:	38 stations	82,500	34,182	49,758	166,440

gaps in the network as needed. Russia's expansion and upgrade of their network continues, with new deployments announced for the next year at Havana, Cuba and Haifa, Israel. All sites will be co-located with GNSS systems primarily intended to tie the GLONASS monitoring network with that of SLR. This addition will eventually improve tremendously the tie between the SLR- and GNSS-, VLBI-implied frames.

Statistics of the SLR data collected as pass segments during the calendar year 2014 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 the High Earth Orbiters (HEO), GPS, GLONASS, ETALON, GIOVE-A/B, GALILEO, BeiDou, and the Moon.

Of all the active ILRS observatories (~38 in 2014), very few are technically equipped to track retro-reflector arrays on the surface of the Moon or spacecraft orbiting around the Moon. In 2014, only three LLR sites collected ranging data to the Moon: The Observatoire de la Côte d' Azur, France (430 NP), the APOLLO site in New Mexico, USA (212 NP) and the Matera Laser Ranging station in Italy (6 NP). Unfortunately, no NP data were obtained at the McDonald Observatory in Texas, USA. This means that the time series of LLR tracking that ran for four decades at McDonald was interrupted.

The measurement statistics of 2014 (Figure 3) shows that about two thirds of the data have been collected at the French MeO site near Grasse and about one third of the data at APOLLO. Figure 4 illustrates the statistics for the observed retro-reflectors, where a much better coverage of all reflectors could be achieved compared to previous years. Nevertheless, most of the data have been obtained by tracking the big Apollo 15 reflector (56%). Figure 5 shows the entire LLR data set from 1970 to 2014 indicating the

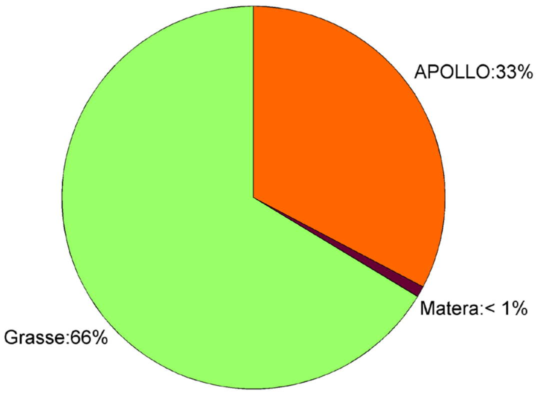

Fig. 3: Observatory statistics in 2014

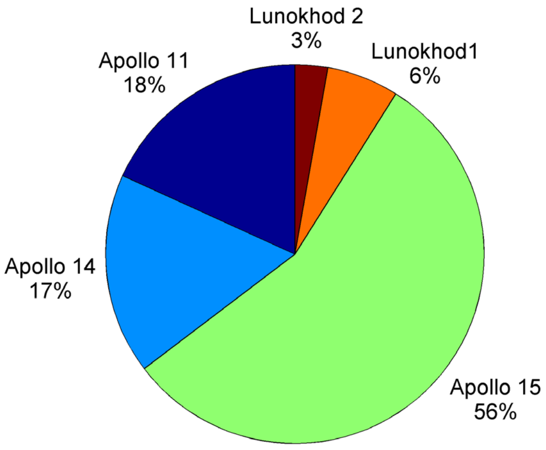

Fig. 4: Retro-reflector statistics in 2014

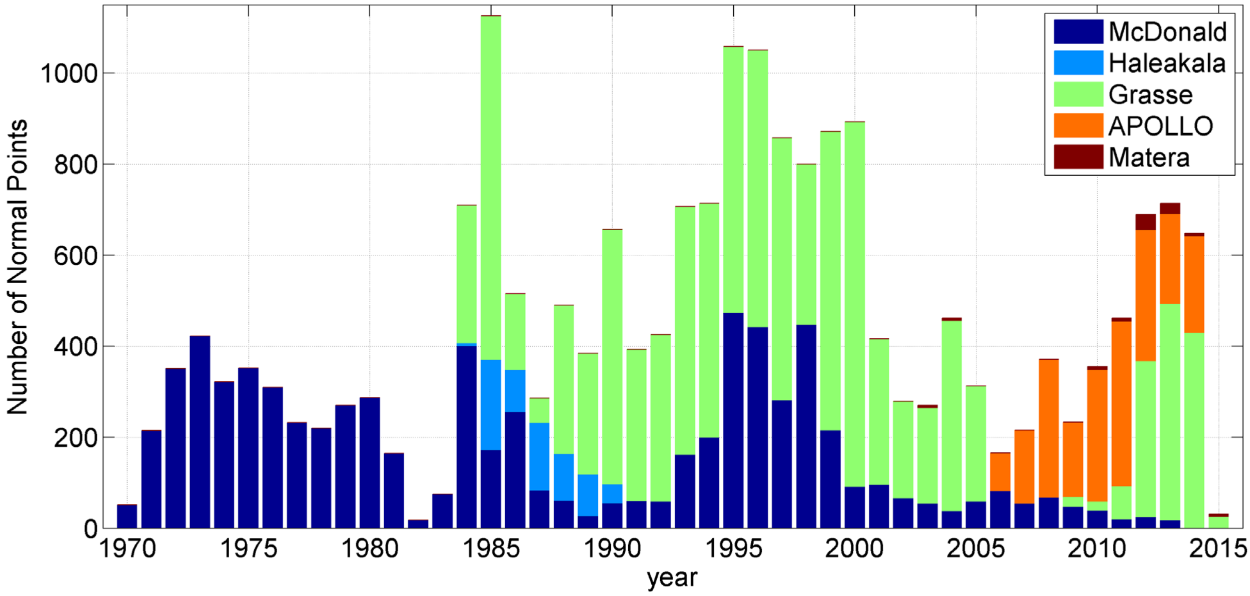

Fig. 5: Data yield of the global LLR network of stations (up to 2014). Note the increasingly significant contribution of Grasse's MeO system upon its return to operations in 2011.

amount of data collected by each of the active LLR sites in each year. It is about 21,000 normal points in total. After several years with less LLR NP, one has reached quite a good level of more than 600 NP per year in the past three years.

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 years, the National Institute for Nuclear Physics (INFN), Frascati, Italy, and the Graduate University for Advanced Studies (SOKENDAI), Japan, increased their activities to analyze LLR data.

One general objective of LLR analysis is to achieve an accuracy level of ~1 mm, today it is still at the centimeter level. The various analysis centers continued their comparison initiative to mutually improve the various codes. Recent activities also comprise comprehensive simulations to show the potential benefit of improved tracking from further observatories and/or to new reflectors, see e.g. Hofmann et al. (2014).

Above all, LLR remains one of the best tools to support lunar science, to study the Earth–Moon dynamics and to test General Relativity in the solar system (Müller et al. 2014). LLR analysis steadily reduces the margins for a possible violation of Einstein's theory of relativity and impressively underpins its validity – now in the 100th year of its existence.

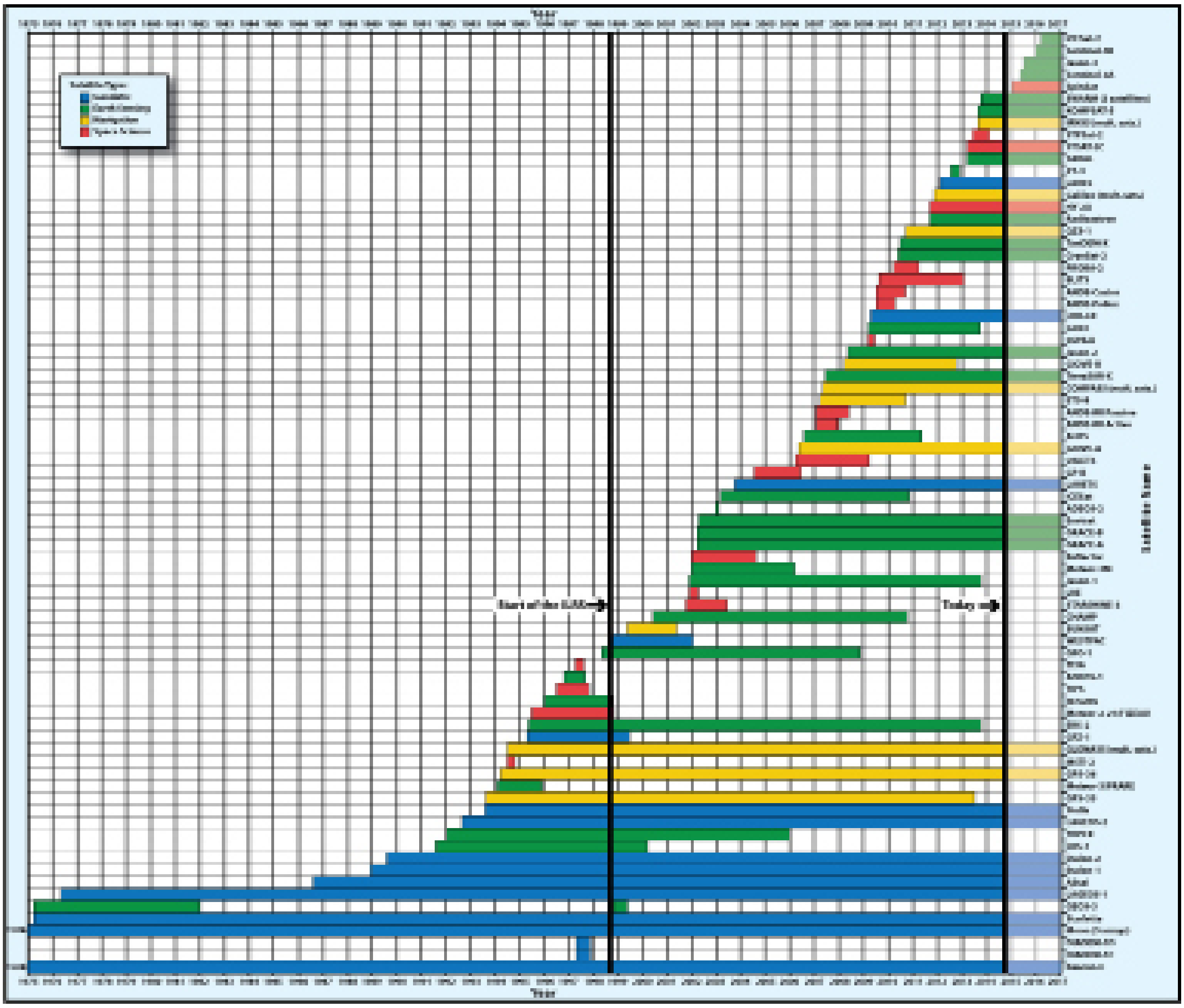

Fig. 6: The currently tracked SLR missions (status as of late 2014).

Missions In 2014, a total of ~38 missions including the Moon (over 70 targets!) were being tracked by SLR/LLR (Figure 6). 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 2014 the steady increase of tracking multiple GNSS targets continued for a fourth 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.

During 2014 the new missions that were launched as shown in Table 2, were primarily spacecraft of GNSS Constellations. SpinSat is an experimental mission with a rather demanding low orbit, requiring special tracking procedures and a good set of predictions,

Table 2: ILRS Supported Missions Launched or Initiating Tracking in 2014.

Satellite Name	Satellite ID	SIC Code	NORAD Number	NP Indicator	Bin Size (sec)	Altitude (Km)	Inclination (deg)	First Data Date
IRNSS-1B	1401701	3302	39635	9	300	42,164	29	2014-Apr-14
GLONASS-132	1401201	9132	39620	9	300	19,140	65	2014-Apr-17
Galileo-201	1405001	7201	40128	9	300	17,300-25,900		2014-Dec-05
IRNSS-1C	1406101	3303	40269	9	300	42,164	29	2014-Oct-09
SpinSat	9806714	1076	40314	1	5	425	51.6	?

including frequent updates to counter the severe atmospheric drag effects it will be undergoing.

Despite the small decrease in active stations in 2014 and a significant increase in tracked targets, the ILRS network has increased its productivity tremendously to maintain the data yield and even significantly increase it (~15%) in comparison to recent years (Figure 7). A major contributor in the recent years' data yield increase is the fact that several stations now track all GNSS satellites. The results of the first GNSS target tracking campaign

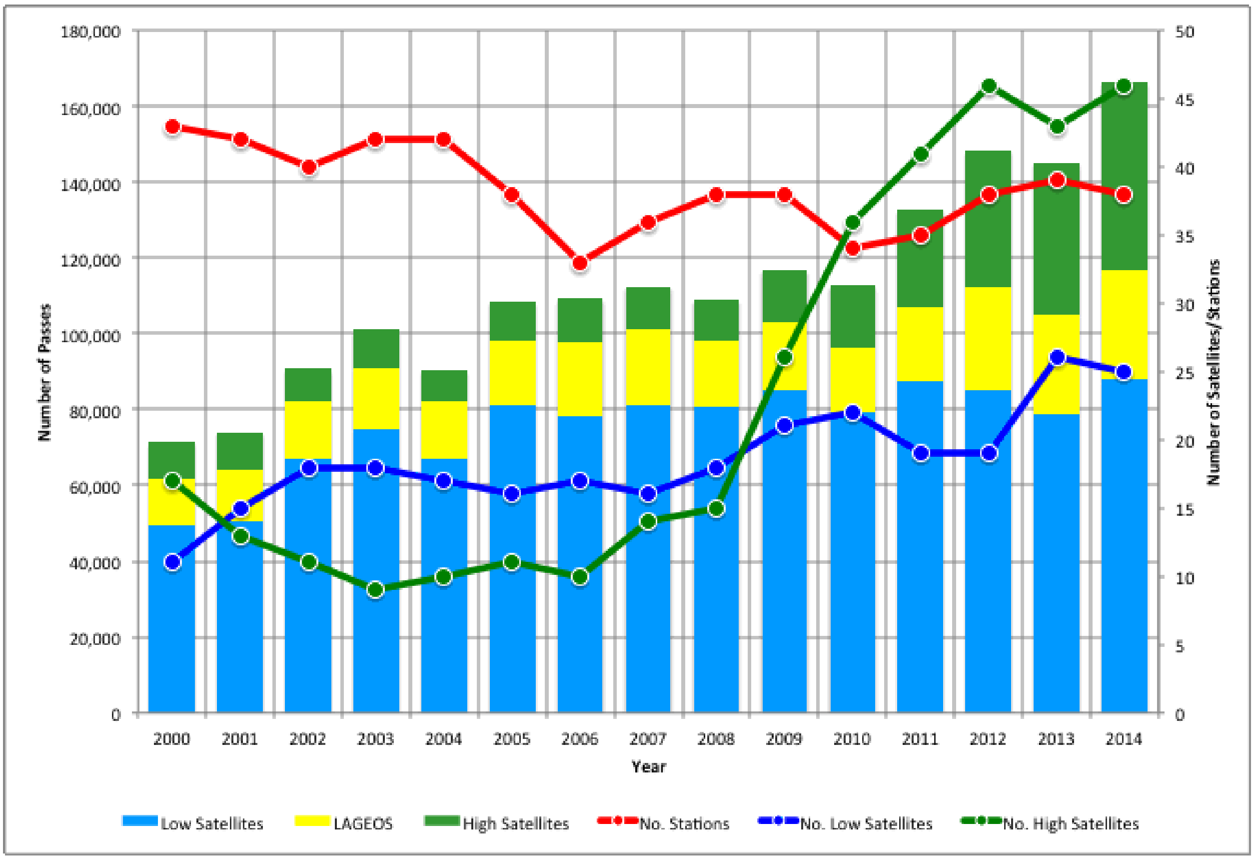

Fig. 7: ILRS network data yield by target type since 2000 (by end of 2014).

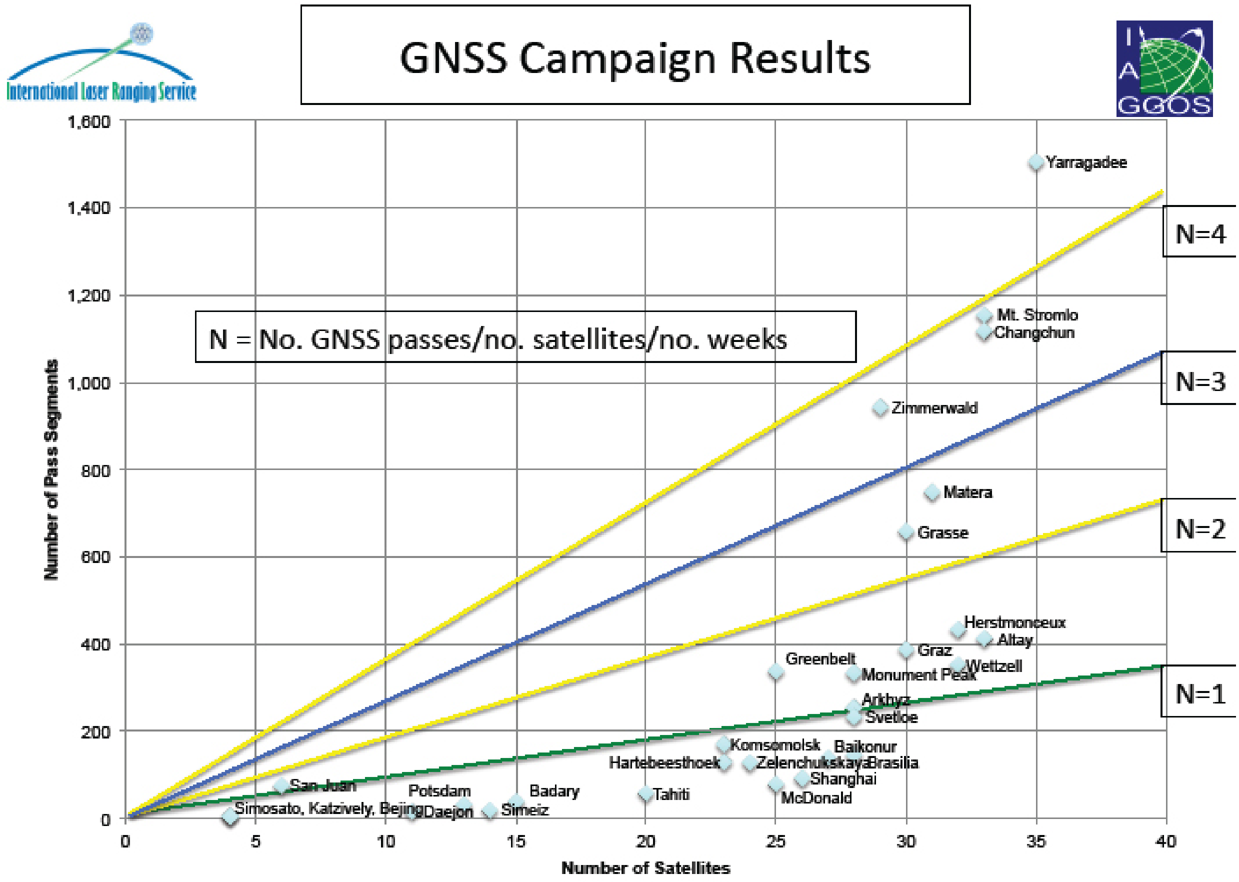

Fig. 8: Tracking data distribution statistics for the first GNSS target tracking campaign (2014).

organized by LARGE Working Group (August through September 2014) indicated that only a few sites were able to track significant number of passes on multiple targets and over the several weeks of the campaign (Figure 8). This prompted the announcement by the ILRS Central Bureau of a follow-on campaign with a more focused set of goals and more frequent reminders to the stations about the importance of meeting these goals. The second campaign started on November 22, 2014 and was initially expected to end by the end of January 2015. This time period however included holidays and less than optimal tracking opportunities, the ILRS CB thus further extended the second campaign to the end of February 2015.

Analysis and science

The Analysis Working Group (AWG) delivered a preliminary version of the ILRS contribution to ITRF2013 just prior to the European Geosciences Union meeting in April 2014. After an initial evaluation by the ITRS Combination Center (IGN), the issues identified were corrected and a new product, based on several ACs providing a

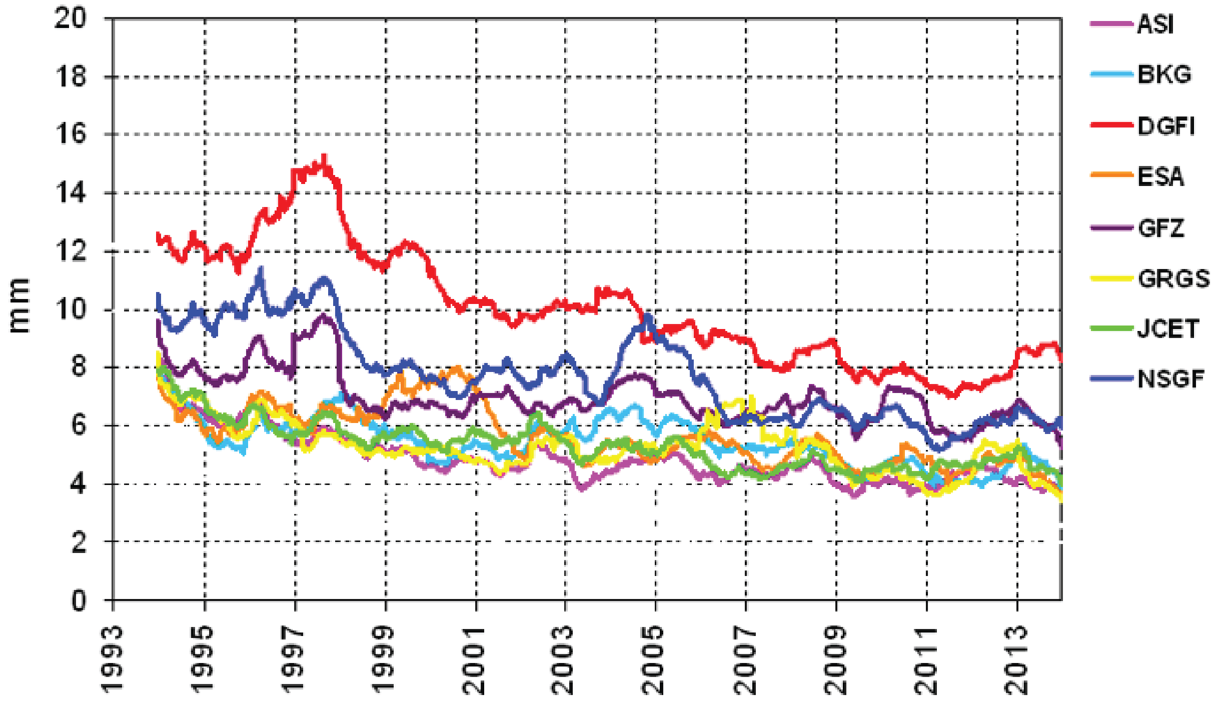

Fig. 9: Three-dimensional weighted RMS in position with respect to the official ILRS-A combination (running mean to demonstrate differences between different ACs).

complete re-analysis of the data, was submitted to the ITRS, in late October 2014, just prior to the 19th International Laser Workshop. The new submission was a significant improvement to the preliminary version, although as seen from Figure 9, there were still some intra-technique issues with some of the contributing ACs. The evaluation of this new version helped in identifying the reasons behind these inconsistencies and the three ACs involved corrected the problems and resubmitted new contributions to be included in the upcoming final combination for ITRF2014 in 2015.

Despite the issues with a few ACs, the delivered ITRF2013 product exhibited a very good quality in the definition of the origin (Figure 10) and the scale of the SLR-only TRF, which were described in a presentation of the ILRS Primary Combination Center (Luceri et al., 2014). The modeling changes and improvements that were adopted prior to the re-analysis for ITRF2013 were detailed in a follow-up presentation (Pavlis et al., 2014). A very small “step” in the time series of TY and the scale, immediately after the beginning of 2010 is under investigation, although it is generally believed to be an artifact of the station geographical distribution.

During the workshop, the ITRS presented an official solicitation for an extension of the new model to include all of 2014, renaming thereby the final product to ITRF2014. All of the ACs present at the workshop agreed to support this extension and meet the new

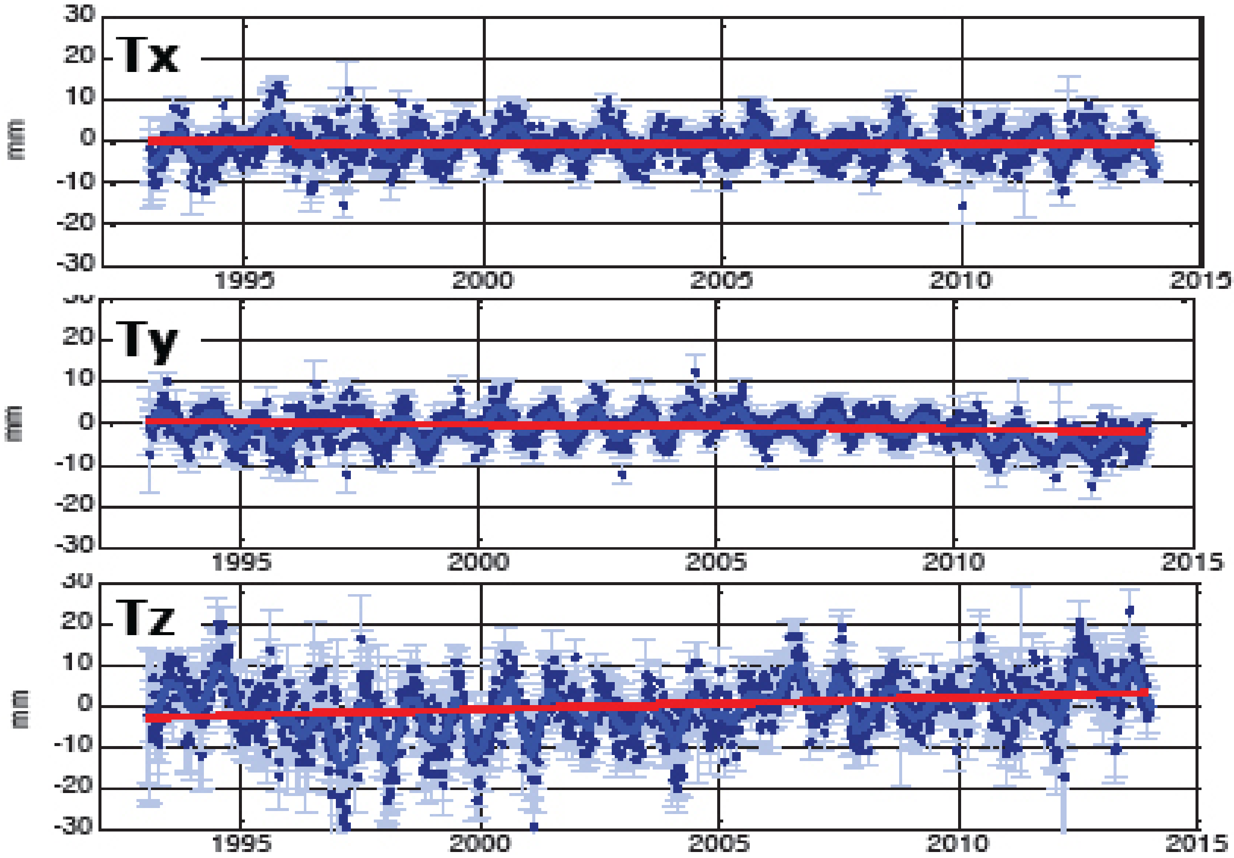

Fig. 10: Weekly variations of the origin with respect to the origin of SLRF2008 (ITRF2008).

deadline for a final ILRS product delivery date of the end of February 2014. Several Pilot Projects (PP) that were to be completed after the ITRF2013 development process, were postponed until after the delivery and finalization of ITRF2014.

Meetings

The ILRS held an extraordinary international laser workshop (19th) in Annapolis, MD, USA, October 26–31, 2014, which was already discussed in the introduction. The first day of the workshop was devoted to talks with a historical perspective, from the pioneers of the technique. NASA and ILRS presented them with awards for their contribution to the establishment of the technique fifty years ago. The awards were presented by the ILRS chairman Dr. G. Bianco of ASI/CGS, Matera, Italy and the ILRS Central Bureau director, Dr. M. Pearlman of the Smithsonian Astrophysical Observatory, Cambridge, MA (Figure 11). The AWG held two meetings in 2014, one prior to the EGU General Assembly, on April 28 (<http://ilrs.gsfc.nasa.gov/science/awg/awgActivities/index.html>), and one prior to the 19th ILW in Annapolis, on October 26 (<http://ilrs.gsfc.nasa.gov/science/awg/awgActivities/index.html>). The ILRS Governing Board met once in 2014, during the Anna-

Fig. 11: The surviving team members of the pioneering group that ran the first successful SLR experiment at Goddard, MD on the evening of October 31, 1964. With them are the ILRS Chairman (first on the left) and the ILRS CB Director (last on the right), after the special award ceremony in Annapolis, MD.

polis workshop on October 26 (<http://ilrs.gsfc.nasa.gov/about/organization/govboard/gbmeeting_reports.html>). The ILRS has already announced a Technical Workshop for 2015, to take place the last week of October in Matera, Italy. Furthermore, in 2016, the 20th International Laser Workshop will take place in Potsdam, Germany, hosted by GFZ.

Publications

Access all the presentations, posters, and proceedings papers presented at the 19th International Laser Workshop in Annapolis, MD from the official ILRS page for the workshop:

<http://cddis.gsfc.nasa.gov/lw19/Program/index.html>

Hofmann, F., J. Müller, L. Biskupek, Mai, E., and Torre, J.-M.: Lunar Laser Ranging – What is it Good for? Proceedings of the 18th International Workshop on Laser Ranging, Fujiyoshida, Japan, 11–15 November 2013, Contribution No. 13-0402, 2014 (available on ILRS meeting website).

Luceri, V. E. C. Pavlis, D. König, B. Pace, M. Kuzmicz-Cieslak, and G. Bianco: The ILRS Contribution to the Development of ITRF2013, 19th International Workshop on Laser Ranging, Annapolis, MD, October 26-31, 2014 (available on ILRS meeting website).

Müller, J., L. Biskupek, F. Hofmann, and E. Mai: Lunar Laser Ranging and Relativity. Book chapter in “Frontiers of Relativistic Celestial Mechanics”, vol. 2 (ed. by S. Kopeikin), de Gruyter, p. 99–146, 2014.

Pavlis, E. C., V. Luceri, M. Kuzmicz-Cieslak, D. König, and G. Bianco: Modeling Improvements in the ILRS Reprocess for ITRF2013, 19th International Workshop on Laser Ranging, Annapolis, MD, October 26–31, 2014 (available on ILRS meeting website).

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

<http://ilrs.gsfc.nasa.gov/about/reports/biblio/bibliography.2014.html>

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