

### 3.4.2 International Laser Ranging Service (ILRS)

**Introduction** The International Laser Ranging Service (ILRS), established in 1998, is responsible for the coordination of SLR/LLR missions, technique development, network operations, data analysis and scientific interpretation. Here we summarize the status and developments in 2008–2009.

**Network** The network of SLR/LLR stations, under the aegis of the ILRS, has been subject to change over the years. From a technical perspective, the quality of the observations has improved drastically during the past decade. At this moment, the single-shot precision of an average station is better than 10 mm (for the best stations this number is a few millimeters). The absolute quality of the individual observations is at the 10 mm level, with a significant number of stations doing significantly better. The geometry of the SLR network has been a point of concern over the years. However, the network has improved (cf. Figure 1), in part due to the reinstatement of some key-sites that were shut down in 2004 and in 2008 due to the return to action of sites at Maidanak, Komsomolsk and the new Russian site in Altay. Although the network has been dominated traditionally by stations in the Northern Hemisphere, the Southern Hemisphere now contains a number of high-quality stations, that have come online recently or that have developed and proven themselves over the past few years. NASA’s next generation SLR system (formerly known as SLR2000) is in the final stages of development, and it is expected to reach the production line by the end of 2010. Several other stations

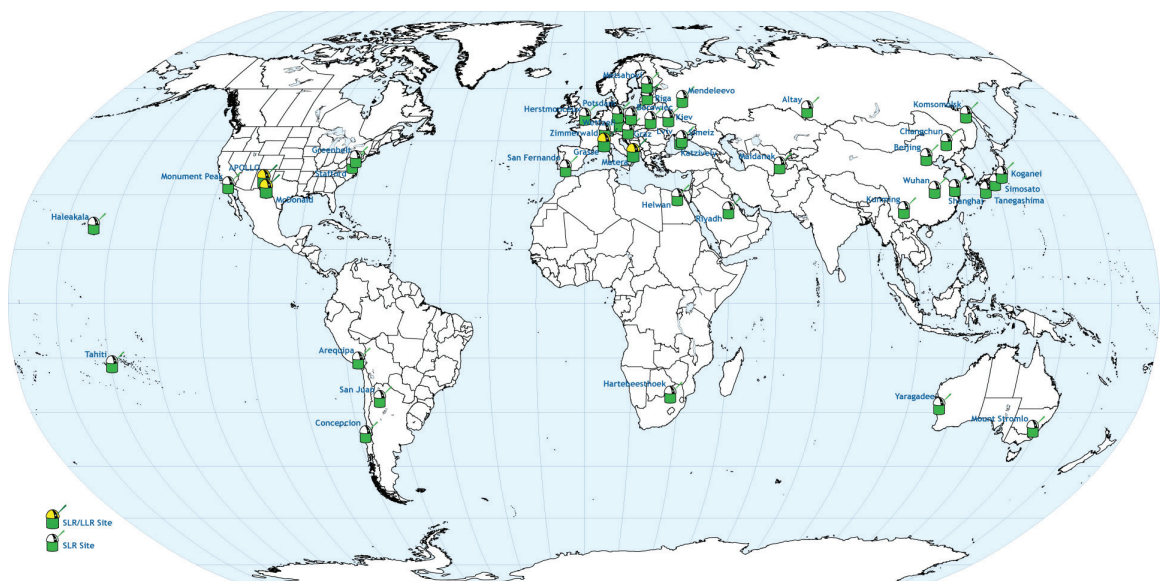


Fig. 1: The global network of SLR stations (status early 2010).

switched to high repetition rate systems, e.g. Herstmonceux, UK; Zimmerwald, Switzerland; Changchun, Shanghai and Beijing in China, and more sites with similar systems will soon be added to the network. This evolution will slowly lead us to the GGOS-era network as described in their GGOS2020 document. Statistics of the data collected as pass segments during the calendar years 2008 and 2009 are summarized in Tables 1 & 2. For each of the contributing stations the tracked passes are broken down in three categories of tracked targets: Low Earth Orbiters (LEO), LAGEOS 1 & 2, and the High Earth Orbiters (HEO) which include the GPS,

Table 1: ILRS Network Tracking Statistics for 2008.

Site Name	Station	Number of Passes			
		Low	LAGEOS	High	Total
Ajaccio (FTLRS)	7848	772	4	0	776
Arequipa	7403	1,426	131	0	1,557
Beijing	7249	1,632	314	113	2,059
Borowiec	7811	143	65	0	208
Burnie (FTLRS)	7370	495	4	0	499
Changchun	7237	4,019	608	441	5,068
Concepcion	7405	1,792	821	355	2,968
Grasse	7845	36	32	9	77
Graz	7839	4,753	654	539	5,946
Greenbelt	7105	3,377	511	250	4,138
Haleakala	7119	1,820	405	0	2,225
Hartebeesthoek	7501	1,200	254	17	1,471
Helwan	7831	23	0	0	23
Herstmonceux	7840	3,956	872	427	5,255
Katzivily	1893	1,187	310	227	1,724
Kiev	1824	725	90	0	815
Koganei	7308	472	125	60	657
Komsomolsk-Na-Amure	1868	0	27	5	32
Kunming	7820	601	61	0	662
Lviv	1831	182	22	0	204
Maidanak	1864	0	3	0	3
Matera	7941	2,880	800	77	3,757
McDonald	7080	1,075	335	243	1,653
Monument Peak	7110	1,548	366	115	2,029
Mount Stromlo	7825	5,979	1,250	448	7,677
Potsdam	7841	1,827	313	7	2,147
Riga	1884	319	58	4	381
Riyadh	7832	3,173	823	383	4,379
San Fernando	7824	3,019	440	72	3,531
San Juan	7406	5,975	1,132	1,475	8,582
Shanghai	7821	1,265	164	29	1,458
Simeiz	1873	820	282	86	1,188
Simosato	7838	123	40	0	163
Tahiti	7124	347	98	10	455
Tanegashima	7358	378	64	85	527
Wettzell	8834	4,455	1,011	366	5,832
Yaragadee	7090	10,481	2,085	1,525	14,091
Zimmerwald	7810	4,276	832	811	5,919
Totals:	38 stations	76,551	15,406	8,179	100,136

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Table 2: ILRS Network Tracking Statistics for 2009.

Site Name	Station	Number of Passes			
		Low	LAGEOS	High	Total
Altay	1879	45	69	95	209
Arequipa	7403	605	12		617
Beijing	7249	766	114	25	905
Borowiec	7811	673	47		720
Changchun	7237	5,211	539	408	6,158
Concepcion	7405	377	108	3	488
Concepcion@847	7405	3,380	1,183	673	5,236
Grasse	7829	101			101
Grasse_MEO	7845	648	474	326	1,448
Graz	7839	4,119	618	464	5,201
Greenbelt	7105	5,175	812	467	6,454
Haleakala	7119	1,832	457		2,289
Hartebeesthoek	7501	1,660	424	92	2,176
Helwan	7831	6			6
Herstmonceux	7840	3,759	821	434	5,014
Katziwely	1893	1,798	172	290	2,260
Kiev	1824	1,198	98		1,296
Koganei	7308	1,311	288	273	1,872
Komsomolsk	1868	14	38	25	77
Kunming	7820	225	14		239
Lviv	1831	458	28		486
Matera_MLRO	7941	1,876	578	253	2,707
McDonald	7080	1,133	387	262	1,782
Monument_Peak	7110	1,496	322	342	2,160
Mount_Stromlo_2	7825	5,760	1,047	337	7,144
NRL	7865	1			1
Papeete	7124	236	73	18	327
Potsdam_3	7841	2,603	449	88	3,140
Riga	1884	702	91	3	796
Riyadh	7832	1,275	278	144	1,697
San_Fernando	7824	2,915	277	106	3,298
San_Juan	7406	4,512	1,087	1,219	6,818
Shanghai_2	7821	1,306	133	87	1,526
Simeiz	1873	894	167	93	1,154
Simosato	7838	763	224	3	990
Tanegashima	7358	584	128	206	918
Wettzell	8834	4,833	894	348	6,075
Yarragadee	7090	10,434	2,035	1,488	13,957
Zimmerwald@532	7810	6,025	1,209	1,352	8,586
Totals:	39 stations	80,709	15,695	9,924	106,328

GLONASS, ETALON and GIOVE-A/B satellites (GALILEO test s/c), as well as a number of recently launched Beidou satellites, part of the Chinese Navigation Constellation COMPASS. There are some additional experimental satellites at HEO orbits (e.g. JAXA's ETS-8) that are only tracked by part of the network due to their geographical coverage limitations.

From all of the ILRS observatories (nearly 40), there are only a few sites that are technically equipped to carry out Lunar Laser

Ranging (LLR) to retro-reflector arrays on the surface of the Moon (Figure 2) or spacecraft orbiting around the Moon. The McDonald Observatory in Texas, USA and Observatoire de la Côte d'Azur, France were the only operational LLR sites over the past few years, achieving a typical range precision of 18–25 mm. The latter underwent renovation since late 2004, and returned to action in September 2009. A new site with lunar capability has been built at the Apache Point Observatory, New Mexico, USA, equipped with a 3.5 m telescope. This station, called APOLLO, is designed for mm accuracy ranging. A new set of data from APOLLO was released in 2009, with about 640 normal points available in total. The APOLLO data shall soon be provided in the newly adopted ILRS data format (CRD). The data distribution of all LLR observatories is shown in Figure 3.

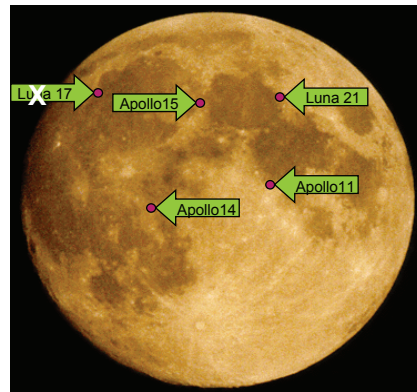


Fig. 2: Retro-reflector sites on the Moon, Luna 17 has not been successfully tracked until 2009.

Table 3: Values from LLR for some relativistic parameters and their realistic errors.

Nordtvedt parameter $\eta$ (test of the strong equivalence principle)	$(6 \pm 7) 10^{-4}$
time variable gravitational constant $\dot{G}/G$ [yr <sup>-1</sup> ] $\ddot{G}/G$ [yr <sup>-2</sup> ]	$(2 \pm 7) 10^{-13}$ $(4 \pm 5) 10^{-15}$
preferred frame parameters $\alpha_1$ $\alpha_2$ (coupled with velocity of the solar system)	$(-4 \pm 9) 10^{-5}$ $(2 \pm 2) 10^{-5}$
preferred frame parameter $\alpha_1$ (coupled with dynamics within the solar system)	$(1.6 \pm 4) 10^{-3}$

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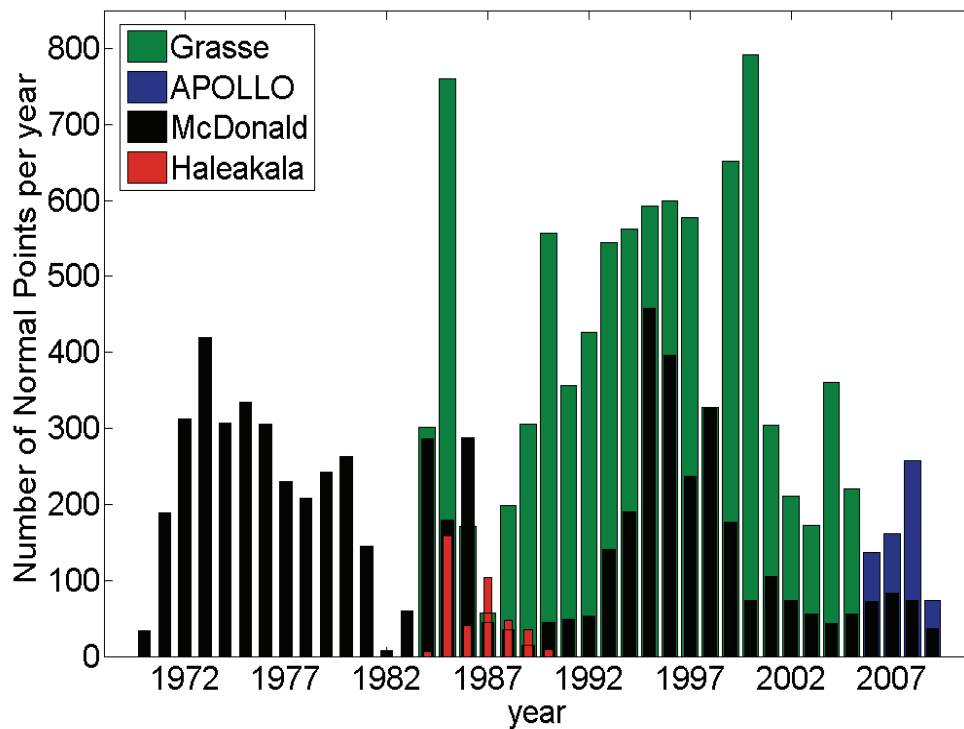


Fig. 3: The LLR NP data collected at all LLR observatories from 1970 until 2009.

There are now plans for the Matera, Italy and the new Wettzell, Germany stations to join the LLR tracking network in the near future, in addition to the already announced intentions of the Mt. Stromlo, Australia station, as well as the plans for establishing a lunar capability at the South African site of Hartebeesthoek, once a new telescope is installed. Today, the results from LLR are considered among the most important science return of the Apollo era. Lunar laser ranging has continuously provided range data for about 40 years, generating about 16800 normal points. Based on appropriate modeling and sophisticated data analysis, LLR determines many parameters of the Earth-Moon dynamics like lunar ephemeris, lunar physics, the Moon's interior, reference frames and Earth orientation parameters.

LLR has also become the strongest tool for testing Einstein's theory of general relativity in the solar system. By extending the standard solution, it is possible to solve for parameters related to gravitational physics, like the temporal variation of the gravitational constant, metric parameters as well as the strong equivalence principle and preferred-frame effects (Soffel et al., 2008). The latter can be related to gravito-magnetic effects in the solar system constraining possible deviations from Einstein's theory. Recent results for some selected relativity parameters including realistic errors are given in Table 3.

Even further predictions of general relativity (secondary effects), which were not fit for in the past, can be investigated, e.g., those parameterizing effects of modifications of Einstein's theory. In addition, quantum physical predictions, assuming Lorentz violation, which will manifest itself as oscillatory perturbation of the lunar orbit, can be determined.

The moon is also investigated with dedicated lunar orbiters. One of them is the Japanese mission Kaguya (Selene) launched in 2007. Its data were used to produce a lunar map with unprecedented accuracy and spatial resolution, especially of the far side of the Moon.

**Missions**

In 2008–2009, a total of ~30 satellites (including the Moon) were being tracked by laser (Figure 4). During 2008 the ILRS completed its effort to develop a standardized design for retro-reflector arrays on future missions. The basic principles adopted will provide guidelines for future designs that will yield guaranteed results in the quality and quantity of tracking data. Year 2008 was a year of several new missions launched with retro-reflector arrays. On April 26 GIOVE-B was successfully placed in orbit. On June 20, Jason-2/OSTM was launched as follow-on to the successful oceanographic radar-altimeter-carrying satellites TOPEX/POSEIDON

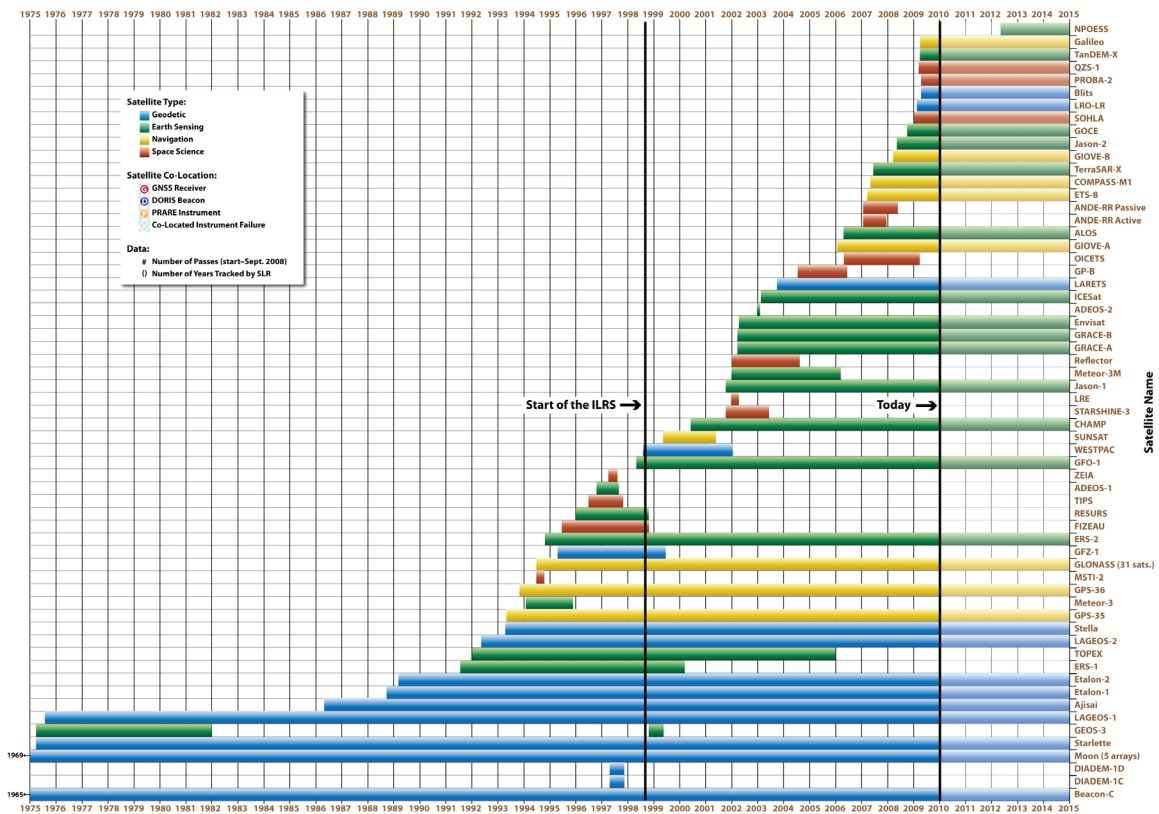


Fig. 4: The currently tracked SLR missions (status early 2010).

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and Jason-1. One of the exciting facets of this mission is the T2L2 time synchronization experiment carried onboard, something that will generate new interest in tracking this target. The year concluded with the launch of two triplets of GLONASS spacecraft, one on September 25 and one on December 25, placing in orbit the six M-type spacecraft that occupy the slots 110 through 115. The new satellites improved significantly the service provided by GLONASS and ILRS selected three of the M-type s/c to be tracked routinely for orbit calibration purposes (102, 109, 115). During 2008 we also lost some targets due to decay or loss of scientific interest after failure of the main instrumentation. After a successful tracking campaign, Naval Research Lab's (NRL) ANDE-RRP (Atmospheric Neutral Density Experiment Risk Reduction – Passive component) mission re-entered on May 25, 2008. The other half of the mission, the active spacecraft ANDE-RRA, had already re-entered on Dec. 25, 2007. Sometime in late September GFO-1 went into safe mode and after unsuccessful attempts to right the spacecraft, operations terminated on September 25, 2008 and along with that tracking by the ILRS network. In late 2008 the ILRS network started tracking of the COMPASS M1 satellite, a component of the new Chinese Navigation Constellation Beidou (COMPASS).

Over 2009, ILRS continued preparations for several demanding new missions to be launched in the near future. One of them, the Lunar Reconnaissance Orbiter (LRO), carries multiple laser technology components: a laser altimeter (LOLA) for topographic mapping and a laser transponder for one-way laser ranging (LR). One goal is to take photographs of the old landing sites. After careful planning and coordination with stations that showed interest in participation, the project has arrangements with a significant number of the ILRS sites to participate in tracking LRO-LR that eventually launched successfully on June 17, 2009.

On March 17, 2009 (exactly seven years after the date of the GRACE mission launch!), the new gravitational mapping mission GOCE of ESA was successfully launched and soon after it was tracked by the ILRS network. The GOCE mission, due to its very low orbiting altitude—295 km!, put to test the predicting and tracking facilities of ILRS. It was a pleasant surprise to see that the systems worked perfectly in all areas and provide continued support to the mission through all of its phases.

The last launch of 2009 with ILRS interest was that of BLITS (Ball Lens In The Space), an experimental satellite launched by the Federal Space Agency of Russia (Figure 5). As the name of the mission implies, this is a very novel design of two concentric glass balls (one contained in the other) with slightly different refractive indices that result in turning these balls into a spherical retro-reflector with a very precisely known signature. The results

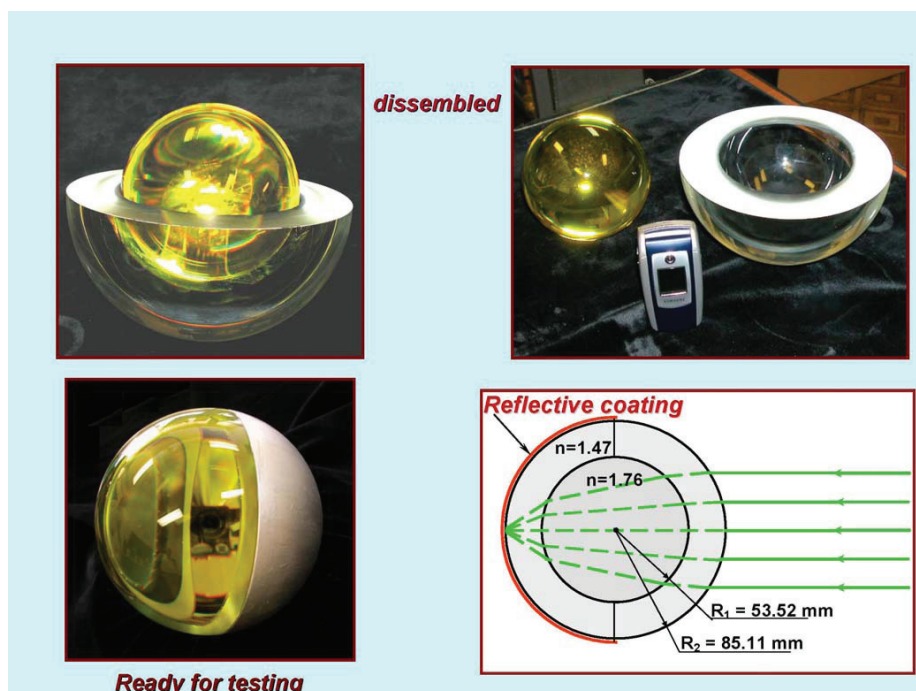


Fig. 5: The BLITS (Ball Lens In The Space) spacecraft design (courtesy FSUE IPIE).

of the initial tracking data indicate that this type of design has the potential to cover the needs of GGOS for very low and stable target signature satellites for extremely accurate reference frame applications.

Several dedicated tracking campaigns were successfully executed during 2008 and 2009. Three of them involved one or both of the GIOVE spacecraft and a fourth one targeted the two aging GPS spacecraft that carry retro-reflectors (GPS-35 & 36), as they were nearing their operational lifetime. In mid-2008, GPS-35 was set “unhealthy” in the US Navigation bulletins and ILRS ceased tracking operations. This left us with only one GPS satellite with laser retro-reflectors onboard. Other dedicated campaigns tracked the IceSAT/NASA and OICETS/JAXA missions.

### Analysis and science

The main topic on which most of the Analysis Centers focused their work during 2008 was the preparation of the ILRS submission to ITRS for the development of ITRF2008. As it was already planned since the development of ITRF2005, ILRS' Analysis Working Group (AWG) was to extend their analysis period to cover the interval 1983 to present. This would provide a much longer record for some sites with long histories and it would generate new, improved coordinates and velocities for several sites that were active in the early years of SLR but no longer exist. The primary concern of all AC analysts was the meticulous treatment

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of measurement biases, known from engineering tests or detected during the analysis. With the accuracy of the results reaching a few millimeters at worst, even small biases of comparable magnitude cause discontinuities in the TRF and force the introduction of ad hoc “breaks” in the series which must be avoided at all costs since they cause instability in the end-product.

An initial analysis was submitted to ITRS near the end of 2008, which upon their preliminary analysis served as the basis for the final submission (in mid-2009), taking into account the feedback from ITRS. The final version of the ITRF2008 was not released in 2009 as planned, but an extensive evaluation and validation period of the preliminary version proved very useful for the improvement of future realizations. Figure 6 shows the offsets of the origin and scale components for the data period included in the ILRS contribution to ITRF2008 (1984 – 2009). The newly added period of historical data (1984 to 1992) is based on LAGEOS data alone and ground systems with much less accurate data than the present network, which are the reason behind the large and often systematic behavior during the early years.

The corresponding components for the period 1993 to 2009 are based on data from LAGEOS 1 & 2, as well as data from the ETALON 1 & 2 after 2002. It is evident that the contribution of additional targets helps considerably to stabilize the series and the improved data quality results in demonstrating mainly seasonal signals of geophysical origin. One of the significant improvements of this re-analysis was the compilation and validation of a complete set of measurement biases at all sites, which was put in a SINEX-like standardized format and will be from now on the basis

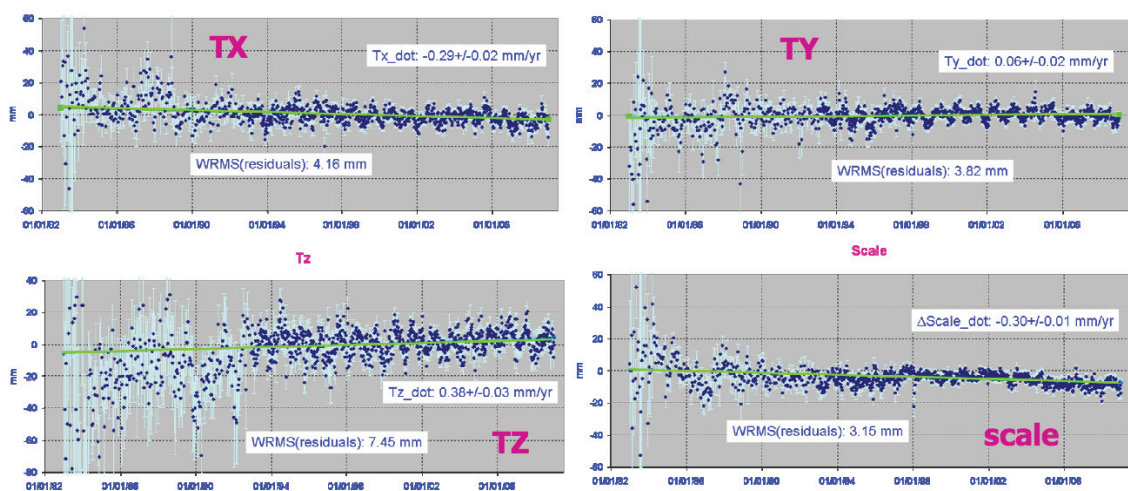


Fig. 6: Time-series of X, Y, and Z offsets and scale factor averages of the ILRS-A official combination origin with respect to the reference TRF (SLRF2005) origin (proxy for “geocenter” variations) and scale as observed by SLR (1984.0 – 2009.0).

of any SLR data analysis effort. This is also available through the ILRS web pages to any other SLR data analysts, to ensure that the data are correctly treated by anyone user and for any reason, whether it is for ILRS official products or independent research.

During 2008–2009, ILRS continued improving the models and procedures used in the analysis of the range data collected from the ILRS network, and in particular, the accurate determination of the target signature (“center of gravity to effective reflection surface” – CoG). The ILRS-established task forces dedicated to improving the target signature characterization and the communication between tracking stations and the analysts were very active during this period. On several occasions biases detected at sites were reported within hours and corrective action was taken immediately, to limit the repercussions on the analysis products. Additionally, following the characterization of the LAGEOS targets, the target signature task force adopted a comparable table for the two ETALON satellites. This improved consistency and accuracy of the CoG magnitude will lower significantly the limits of error on the scale definition of the ITRF from SLR.

The SLR observations find their way into many cutting-edge science studies: reference frames (origin and scale), crustal deformation (relative motions), long wavelength static and time varying gravity field (direct inversion and/or calibration of solutions derived with other techniques), oceanography (sea-level change, tides), earth rotation (observation of relevant parameters), orbital mechanics (satellite motion), and fundamental physics (gravitational theory tests), to name a few. A number of these aspects will be highlighted below.

Some of the ILRS analysis products are of particular interest to IERS, either as input to Earth Orientation Parameter (EOPs) predictions or the development of the ITRF. In particular, SLR plays a uniquely important role in the definition of the origin of the ITRF and its scale. The laser technique provides unique information on the exact location of Earth’s geocenter with respect to the tracking network and along with VLBI, its absolute scale. The root-mean-square (RMS) of the weekly X-Y-Z offsets and  $\Delta$ -scale is 4 mm, 4 mm, 7 mm and 3 mm, respectively, for the 1984–2009 period. Statistics for the more recent period are by far better.

Since 2003, the ILRS AWG submits on a weekly basis their products to IERS every Wednesday evening (UTC). From the “operational” point of view, the combination solutions are used for a variety of purposes: the IERS Combination Pilot Project, the IERS/NEOS Bulletin A, etc. From a less frequently updated product, they were vital in the development of the new ITRF every few years. In order to fulfill the need of NEOS for as “fresh” as possible EOP information, the ILRS AWG decided in late 2007 to develop a new

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“daily” product, based on a 7-day arc sliding by one day each day. The results of this analysis are available to NEOS less than two days from the last observation in the analysis with efforts underway to further decrease this latency period. During 2008-2009, six ACs (ASI, BKG, GFZ, GRGS, JCET and NSGF) contributed to the Pilot Project for this daily product, with more ACs expected to join the group in 2010. A NEOS evaluation of the new product indicates that the quality is now nearing that of the weekly product, which is based on the contributions from eight ACs. The ILRS will decide in 2010 whether to evolve this PP into an official product (replacing the weekly one), or to discontinue it.

During 2009 the European Space Agency Space Operations Center (ESOC) underwent benchmark activities to become an official ILRS Analysis Center under the codename “ESA”. Most of the testing formalities were successfully completed at the end of 2009, so it is expected that in early 2010, ESA will be accepted as the ninth member of the official ILRS Analysis Working Group.

#### **Meetings**

The ILRS held a number of meetings over the 2008-2009 period. In 2008 we convened the 16<sup>th</sup> International Laser Workshop at Poznań, Poland, with the theme “SLR – the next generation”. The very successful workshop was attended by most of the ILRS members and associates and the proceedings were published in two volumes.

<[http://www.astro.amu.edu.pl/ILRS\\_Workshop\\_2008/index.php](http://www.astro.amu.edu.pl/ILRS_Workshop_2008/index.php)>

Recognizing the increasing number of navigation constellations that rely heavily on SLR to calibrate and support their operations, in the fall of 2009 we organized the ILRS Technical Workshop on “SLR Tracking of GNSS Constellations”. The workshop, which took place in Metsovo, Greece, September 14–19, 2009, brought together the GNSS and SLR communities in order to understand, plan and propose synergistic collaborations that will help GGOS meet its goals in the coming years.

<[http://www.ntua.gr/MIRC/ILRS\\_W2009/](http://www.ntua.gr/MIRC/ILRS_W2009/)>

In addition to these two main events, the ILRS participated in several international meetings and held several internal meetings of its Central Bureau, Governing Board and the various Working Groups.

<[http://ilrs.gsfc.nasa.gov/about\\_ilrs/meetings.html](http://ilrs.gsfc.nasa.gov/about_ilrs/meetings.html)>

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*Erricos C. Pavlis, Jürgen Müller*