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. The following summarizes the status and developments in 2006.

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 (the best stations go well below that number). Also, the absolute quality of the individual observations is at the 10 mm level, with a significant number of stations doing better. The geometry of the SLR network has been a point of concern over the years. However, as of 2006 the layout of the network has improved (cf. Figure 1), in part due to the reinstatement of some key-sites that were shut down in 2004. 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. In French Polynesia, Tahiti is slowly coming back online; in South America, Arequipa, Peru has returned, whereas Concepcion and San Juan are in operational service; in South Africa, Hartebeesthoek has proven

Fig. 1: The global network of SLR stations (status early 2007).

itself to be a highly reliable, top-quality, productive station; and in Australia the Mt. Stromlo station is a role model for modern, autonomous operations. The contributions from stations in the Southern Hemisphere are of course complemented by the activities of Yarragadee, on the West coast of Australia, which has been the number one station in the network on many different aspects for a long time now. Graz has continued operations with the first 2 kHz system of the network, providing impressive "pictures" of the reflector arrays on geodetic satellites like the two LAGEOS. 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 2008. Several other stations are also looking into acquiring high repetition systems (e.g. Herstmonceux, UK, Zimmerwald, Switzerland). Statistics of the data collected during the calendar year 2006 are summarized in Table 1, in terms of pass segments. For each of the contributing stations the tracked passes are broken down in three categories as far as the tracked targets: Low Earth Orbiters (LEO), the two LAGEOS satellites, and the High Earth Orbiters (HEO).

Among the more than 30 ILRS observatories, there are only a few sites that are technically equipped to carry out Lunar Laser Ranging (LLR) to the Moon (Figure 2). The McDonald Observatory in Texas, USA and Observatoire de la Côte d' Azur, France are the only currently operational LLR sites achieving a typical range precision of 18–25 mm. The latter is actually undergoing renovation since late 2004, which leaves only one site currently operational over the

Fig. 2: The ILRS stations with lunar capability (status early 2007).

Table 1: ILRS Network Tracking Statistics for 2006

		Number of Passes			
Site Name	**Sta.**	**LEO**	**LAGEOS**	**HEO**	**Total**
Arequipa	7403	257	37	0	294
Beijing	7249	1,338	178	91	1,607
Borowiec	7811	695	99	4	798
Changchun	7237	3,309	429	340	4,078
Concepcion	7405	1,202	591	72	1,865
Graz	7839	5,095	862	528	6,485
Greenbelt	7105	1,807	271	103	2,181
Greenbelt	7130	75	27	0	102
Haleakala	7119	130	24	0	154
Hartebeesthoek	7501	2,604	724	210	3,538
Helwan	7831	18	0	0	18
Herstmonceux	7840	3,548	930	384	4,862
Katzively	1893	671	80	27	778
Koganei	7308	228	63	16	307
Lviv	1831	47	0	0	47
Maidanak	1864	739	207	229	1,175
Matera	7941	2,680	874	193	3,747
McDonald	7080	1,115	373	334	1,822
Monument Peak	7110	4,239	899	305	5,443
Mount Stromlo	7825	5,050	1,433	634	7,117
Potsdam	7841	2,077	308	0	2,385
Riga	1884	1,056	98	8	1,162
Riyadh	7832	3,978	979	754	5,711
San Fernando	7824	1,784	261	0	2,045
San Juan	7406	3,846	1,134	882	5,862
Shanghai	7821	1,217	105	7	1,329
Simeiz	1873	433	66	2	501
Simosato	7838	1,887	442	7	2,336
Tahiti	7124	541	154	0	695
Tanegashima	7358	228	31	25	284
Wettzell	8834	4,775	984	485	6,244
Yaragadee	7090	8,999	2,044	1,330	12,373
Zimmerwald	7810	5,175	1,181	850	7,206
Totals:	33 stations	70,843	15,888	7,820	94,551

past two years. 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 first set of ~70 normal points taken over April to December 2006, was made available recently. The data look very promising.

The Australian station at Mt. Stromlo is expected to join this group in the future, and there are plans for establishing a lunar capability at the South African site of Hartebeesthoek, once there is a new

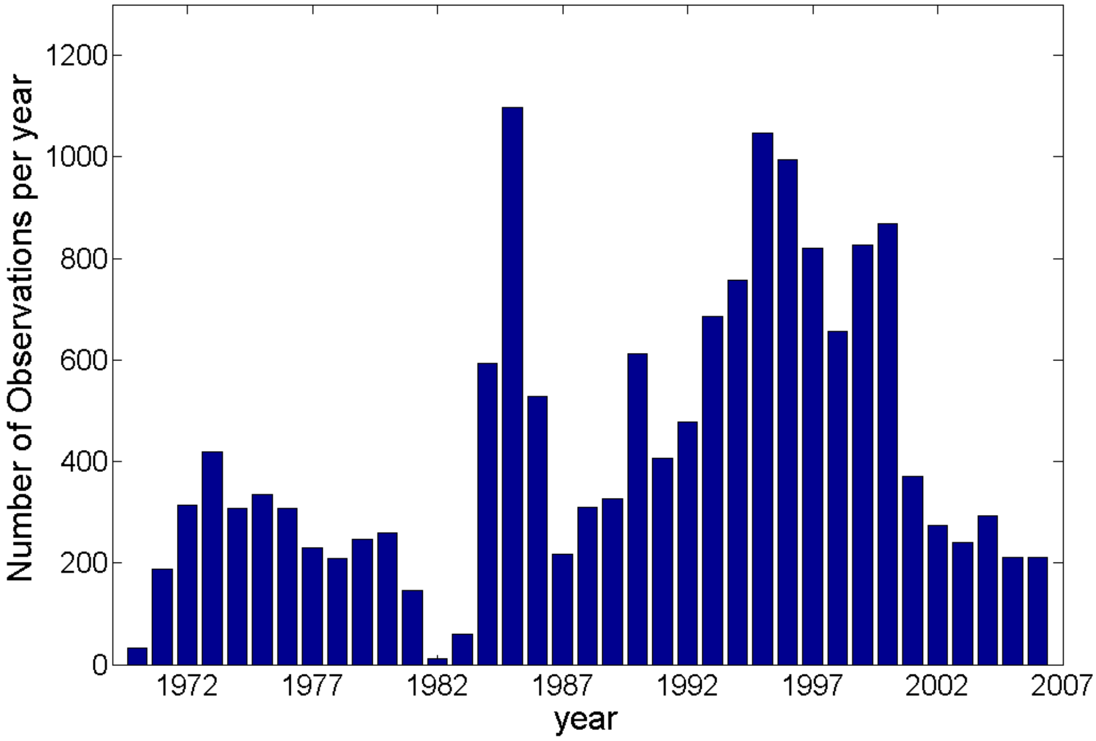

Fig. 3: The currently available LLR data set (status early 2007).

telescope installed. Today, the results from LLR are considered among the most important science return of the Apollo era. The lunar laser ranging experiment has continuously provided range data for more than 37 years, about 15800 normal points, (Figure 3).

The main scientific contributions of LLR are the determination of a host of parameters describing the lunar ephemeris, lunar physics, parameters associated with the Moon's interior, various reference frames, dynamics of the Earth-Moon system, as well as the verification of metric theories of gravity and gravitational physics, such as the equivalence principle or temporal variation of the gravitational constant. Even with current technology, LLR is an extremely challenging measurement task. For more details about the ILRS network, see the ILRS Annual Report 2005-2006: <http://ilrs.gsfc.nasa.gov/reports/ilrs_reports/ilrsreport_2005.html>

Missions

In 2006, a total of ~30 satellites (including the Moon) were being tracked by laser (Figure 4). In late 2005, three new GLONASS s/c were placed in orbit: GLONASS-98, -99 and -100. On December 28, 2005, the first test satellite of the future European satellite navigation system Galileo: GIOVE-A, was also launched. In 2006, three more GLONASS s/c were placed in orbit: GLONASS-101, -102, and -103. The emphasis of these new missions is on navigation, SLR however is still recognized as a failsafe, proven POD technique and almost all navigation constellations plan to carry retroreflectors. The ILRS devoted considerable effort and resources during 2006 to develop a standardized retrorefrector design for such missions, in an attempt to improve data quality in the future and ensure adequate tracking for these missions. In December of 2006, three more satellites were launched successfully: JAXA's geostationary ETS-8, an experimental communications, timing and positioning satellite, and Naval Research Lab's (NRL) ANDE-RR, a pair of spherical LEO s/c to support atmospheric density studies and radar calibration. All spacecraft, including the newcomers, are regularly tracked, following a set of dynamically adjusted priorities depending on mission and science demands.

It is noteworthy that two downward-looking satellites, the 2006-launched ALOS, and ICESat, challenged the SLR network with several special requirements (any interference between the laser signal and the instrumentation is to be avoided). Many stations

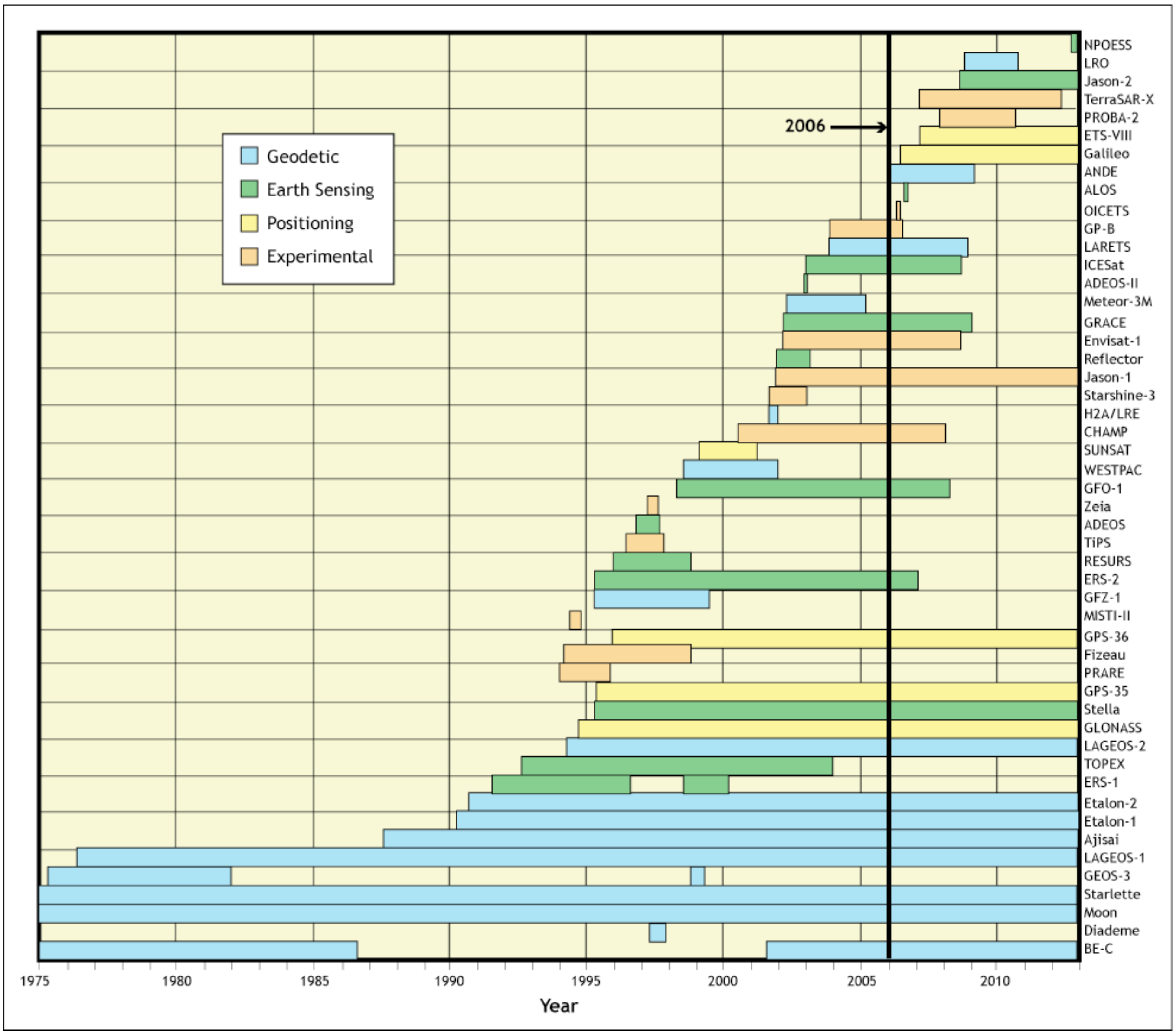

Fig. 4: The currently tracked SLR missions (status early 2007).

responded quickly and carefully to implement special, automated, real-time procedures to ensure safe tracking of these satellites. Tracking of these targets continued very successfully during 2006, resulting in an impressive record of observational passes on both targets.

Analysis and science

SLR provides an extremely valuable and unique tool to relate (the center-of-mass of) satellites to reference points on Earth's surface with unprecedented absolute accuracy: sub-centimeter at present, for about a dozen core sites. Recognizing the importance of this work, ILRS has organized and coordinated its analysis efforts through an Analysis Working Group (AWG). By late 2006, the AWG comprised of seven Analysis Centers (ACs), two Combination Centers (CCs) and several Associate Analysis Centers (AACs). The seven ACs are located at different institutes around the world: ASI/Italy, BKG/Germany, DGFI/Germany, GA/Australia, GFZ/Germany, JCET/USA and NSGF/UK. ASI (primary) and DGFI (backup) are the two CCs responsible with the combination of the contributions of the ACs into a single official ILRS product, following quality checks of the individual contributions and a thorough evaluation of the result. The majority of the AACs focus on restricted data sets, usually associated with a particular mission or world region. A number of

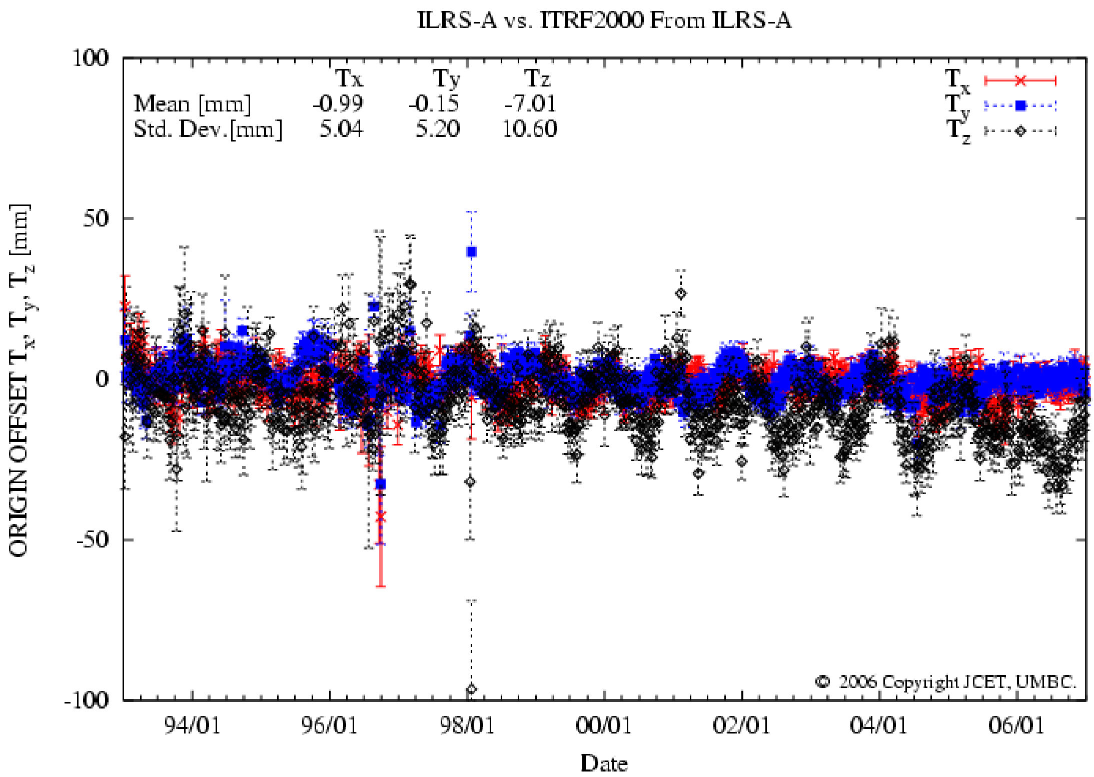

Fig. 5: Time-series of weekly solutions' origin offsets in X, Y, and Z, with respect to the ITRF2000 origin (proxy for "geocenter" variations) as observed by SLR (1993.0 – 2007.0).

them offer a quality control service for the entire network yield on a weekly basis.

During 2006, ILRS continued improving the models and procedures of the range data collected from the ILRS network. A new atmospheric delay correction model was adopted [Mendes and Pavlis, 2004], which was also adopted by IERS as part of the IERS Conventions. A major effort in assessing current as well as historical data biases at all of the tracking sites netted a wealth of information that has now become part of the standard information data set used in any reanalysis of the data. One such cycle was completed in late 2006, however, it was later discovered that due to the existence of additional engineering biases at a number of key sites, the reanalysis must be repeated in 2007. 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 the Earth's geocenter with respect to the tracking network (Figure 5) and along with VLBI, its absolute scale (Figure 6). Figures 5 and 6 display strong seasonal effects, but systematic effects are absent, except for a dip in Tz during 2006 (result of a known by now bias), and the trend in Tz (~ –1.8 mm/y), which is an error in ITRF2000 rather than in the current analysis. The root-mean-square (RMS) of the weekly X-Y-Z offsets and Δ-scale is 5.0 mm, 5.2 mm, 10.6 mm and 0.68 ppb, respectively, for the fourteen-year period. The same statistics for the more recent, 2006 period alone, are: 2.8 mm, 2.2 mm, 6.5 mm and 0.51 ppb, indicating the steady improvement of analysis products with time.

The ILRS' AWG maintains since 2003 the above time-series of weekly solutions for station coordinates and EOPs: x-pole and y-pole and excess Length of Day (LOD). These solutions are based on SLR data taken on the satellites LAGEOS-1, LAGEOS-2, Etalon-1 and Etalon-2. The organization (of generating these solutions) is such that the backup CC institute is able to take over the role of the primary institute at any time. The combinations were generated without interruptions during all of 2006 on a weekly basis, and were

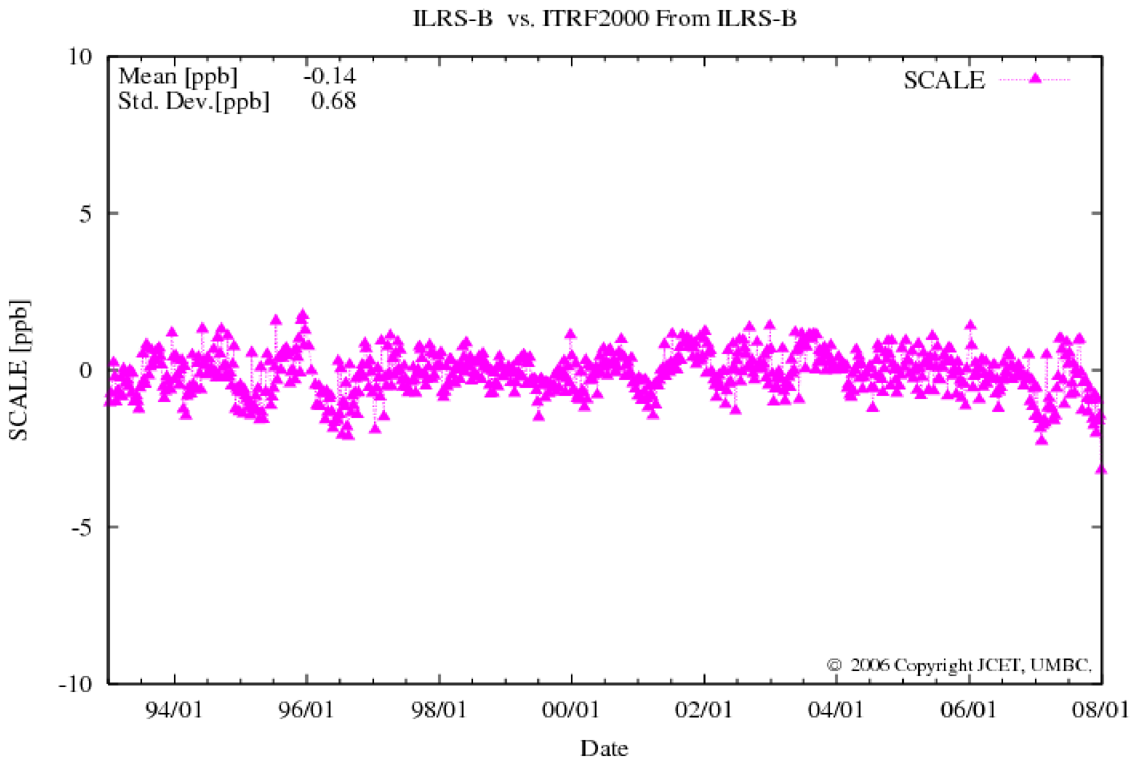

Fig. 6: Time-series of weekly solutions' difference in global scale from ITRF2000 as observed by SLR (1993.0 – 2008.0).

available 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: the ITRF2005 solution, which was based on input from all four geodetic services.

The release of the preliminary ITRF2005P in mid-2006 forced ILRS to spend a significant amount of time and resources to reveal the reasons behind a seemingly significant (~ 1 ppb) scale difference between SLR and VLBI, uncovered during its development. Although SLR was still defining the origin of ITRF2005, it was excluded from the definition of global scale, which was defined entirely by VLBI in ITRF2005. The reasoning that led to this decision is a prime example that consistency is a poor measure of accuracy (biased results can be extremely consistent, though not accurate at all!). As of writing of this Annual Report (late 2007), it is now almost a year since it was discovered that the increased scale discrepancy between the SLR and VLBI contributions were due to an incorrect mean pole tide implementation in some of the VLBI AC contributions (Fig. 7). The incorrect scale of ITRF2005, which is inconsistent with POD efforts, required the development of a "hybrid" version of the ITRF2005, which is scaled back to agree with SLR-implied scale. This was called “ITRF2005 SLR re-scaled”, to avoid confusing it with the original.

To improve the strength, value and reliability of its contribution to future ITRFs, the ILRS has started an effort to extend the time-series of such solutions, and by the end of 2006 it was able to deliver preliminary solutions for the period from September 1983 onwards, the onset of the so-called MERIT campaign (“Monitor Earth Rotation and Intercomparison of Techniques”). With the latest data (since 1993) being reanalyzed with improved models, it was decided to repeat the historical data analysis as well. It is thus expected that by the end of 2007, a new, completely and consistently reanalyzed series of official ILRS products will be available to IERS and the broader community, spanning at least the period September 1983 to end of 2007. However, recognizing the reduced number of satellites available (only LAGEOS), the geometry of the network, the quality of the observations and other aspects, the historical data reanalysis cannot be expected to result in data products that are of similar quality and resolution as what is being obtained from contemporary SLR observations. Nevertheless, this analysis effort

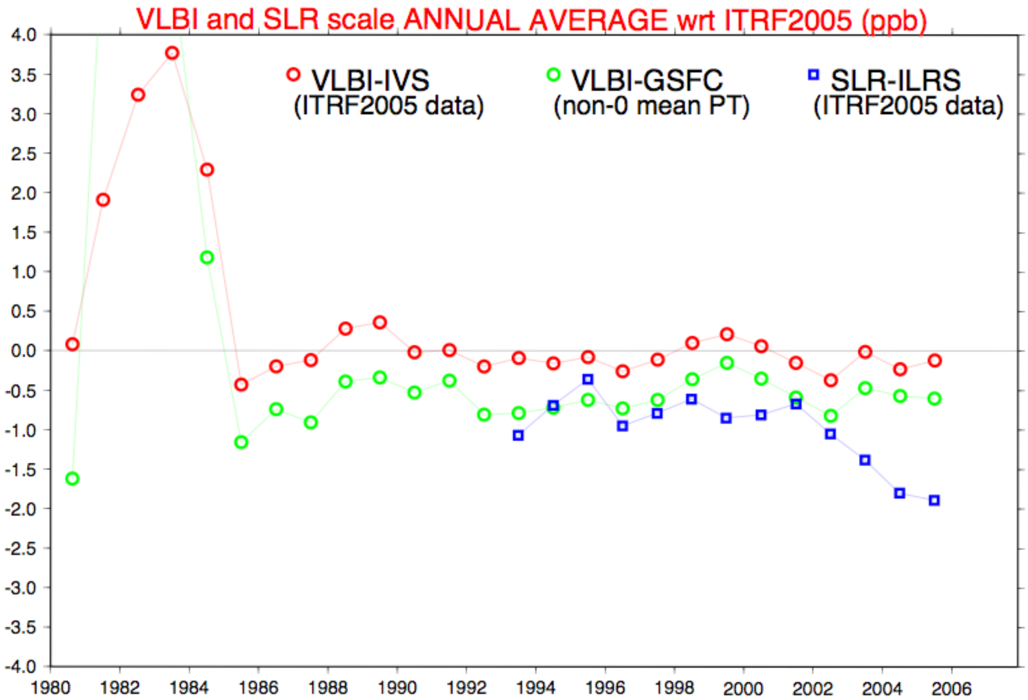

Fig. 7: Annual SLR-VLBI global scale differences with the original IVS contribution to ITRF2005 and one (VLBI-GSFC) using the correct mean Pole Tide formulation. The last 2-3 points of the SLR series indicate a trend, which however is associated with a significant change in network geometry and an erroneous bias application. (courtesy Z. Altamimi/IGN and D. MacMillan/GSFC).

will extend the time-span to 20+ years, and will provide valuable information on some of the most crucial elements of (understanding and describing) System Earth. The weekly products are evaluated during their combination and the results are archived and graphed each week by the JCET AC. Reports for the past weeks as well as the results for the current week for each of the contributing ACs and CCs are available to all via the World Wide Web at <http://geodesy.jcet.umbc.edu/ILRS_QCQA/>.

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