The Global SLR Network and the Origin and Scale of the TRF in the GGOS Era

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Abstract

Satellite Laser Ranging (SLR) data contribute to the realization of the Terrestrial Reference Frame (TRF), defining primarily its origin—geocenter, and in combination with VLBI, its scale. Both entities are fundamental in monitoring vital global change parameters, such as mean sea level, Earth rotation and orientation, etc. The Global Geodetic Observing System (GGOS), places the utmost importance on the development, maintenance and wide distribution of a TRF with very stringent attributes, an origin definition at 1 mm or better at epoch and a temporal stability of 1 mm/y, with similar numbers for the scale and orientation components. The stability, integrity and applicability of the TRF are directly related to the accuracy and fidelity with which mass redistribution can be observed or modeled during its development. Variations in the very low degree and order harmonics, produce geometric effects that are manifested as changes in the origin and orientation relationship between the instantaneous and the mean reference frame.

The unambiguous nature of SLR measurements and absence of significant biases, results in a very precise height determination, and thus the scale of the TRF. SLR has demonstrated millimeter level accuracy for weekly averages. Nevertheless, weather- or failure-induced changes in the network, and the small number and poor spatial distribution of the sites comprising the SLR network, generate additional signals aliased in the results. "Secular trends" seen in the recovered geocenter time series for example cannot be explained by any geophysical phenomena, and are primarily the result of these deficiencies of the present SLR network (poor geometry, lack of redundancy, N-S hemisphere unbalanced distribution, etc.). We investigate here through a number of alternate solutions the robustness of our results, using our SLR analyses spanning the past thirteen years.

Introduction

The Global Geodetic Observing System (GGOS), places the utmost importance on the development, maintenance and wide distribution of an International Terrestrial Reference Frame (ITRF) with very stringent attributes, an origin definition at 1 mm or better at epoch and a temporal stability of 1 mm/y, with similar numbers for the scale and orientation components (Pearlman et al., 2006). The stability, integrity and applicability of the TRF are directly related to the accuracy and fidelity with which mass redistribution can be observed or modelled during its development. Satellite Laser Ranging (SLR) data contribute to the realization of the Terrestrial Reference Frame (TRF), defining primarily its origin—geocenter, and in combination with VLBI, its scale. Both entities are fundamental in monitoring vital global change parameters, such as mean sea level, Earth rotation and orientation, etc., (Altamimi *et al.*, 2002). The motivation behind this contribution was to examine the robustness of the ILRS (Pearlman *et al.,* 2002) contribution to the ITRF in light of the forthcoming developments under GGOS and NASA's effort to upgrade and integrate the space geodetic networks of the future.

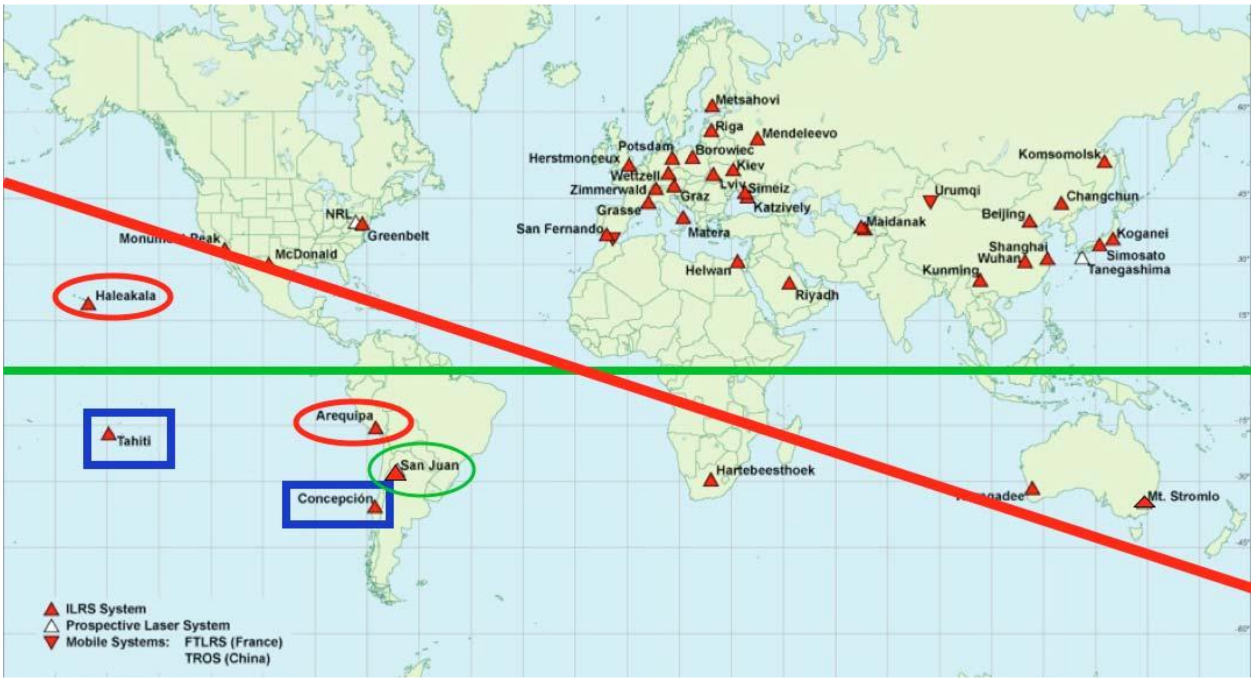

Figure 1. The current ILRS network with mark-ups of sites that were recently established (green), poor-yield southern hemisphere sites (blue),and sites that were shut down in 2004 (red).

SLR contribution to ITRF

The SLR network never achieved an optimal, uniform distribution of stations globally (Figure 1). Furthermore, the closing of two key-sites, Arequipa, Peru and Haleakala, Hawaii in 2004 led to a disastrous lopsided distribution, where one-half the globe is totally void of any SLR observations! This eventually manifested itself in the SLR products as a serious and systematic degradation of the network scale as realized through the SLR observations. Aside from this recent degradation (which is addressed with the re-establishment of the closed down sites and improved performance for the others), this network has produced valuable TRF contributions over the decades. ITRF2000, (Altamimi et al., 2002), was a product that for the first time included a vast number of sites around the world and input from all geodetic techniques with rather strict and rigorous editing in its development. Weekly "geocenter" monitoring with respect to that frame yields a significant and systematic motion in the z-axis, at a rate of ~ 1.7 ± 0.1 mm/yr! Most of this is eliminated in the new realization ITRF2005, but not all. In particular, our SSC (JCET) L 06 analysis resulted in the following rates for the three axes:

$$\Delta x = -6.55 - 0.0848\times(t\text{-}2000) + \textit{periodic terms} \qquad [\text{mm}]$$

$$\Delta y = 4.99 - 0.0898\times(t\text{-}2000) + \textit{periodic terms} \qquad [\text{mm}]$$

$$\Delta z = 0.91 + 1.6981\times(t\text{-}2000) + \textit{periodic terms} \qquad [\text{mm}]$$

The formal accuracy of these estimates is at 0.1 mm/y, however, without an independent estimate to compare, we have no sound way to calibrate this error. Interpreting these signals is even more difficult, since they can be caused by a number of different geophysical phenomena, none of which is easily or fully understood. Table 1 gives some estimates due the main sources that could cause such a systematic signal. It's worth noting that recently, Peltier (private communication), has been able to develop models for Greenland and Antarctica melting in recent times that support this level of "geocenter" motion, especially in the axial component.

***Table 1**. Secular geophysical signals in the axial component of the "geocenter".*

Source	**Magnitude**	**Induced motion**	**Reference**
Sea level	1.2 mm/y	0.064 ± 0.02 mm/y	[2]
Ice sheets (G)	2 mm/y	0.046 ± 0.20 mm/y	[2]
Tectonics	AMO-	0.309 ± 0.05 mm/y	[2]
Postglacial rebound	ICE-3G	0.2 - 0.5 mm/y	[1]

(1) Marianne Greff-Lefftz (2000)
(2) Yu. Barkin (1997)

Methodology

Our conjecture is that the remaining unaccounted-for motion is due to the evolving network, the uneven global distribution of the tracking sites with strong yields, and the poor coverage of some of the major tectonic plates. To test the effect of the "network evolution" we have performed a number of re-analyses of the data, defining TRFs from independent sub-sets of the data in various combinations. As for the effect of the lopsided distribution of the main tracking sites, a large-scale simulation is in progress, within a technique-wide coordinated effort to design the optimal space geodetic networks of the future. The initial results of this investigation will be available by late 2007. A third test involves the so-called effect of the "missing" historical SLR data, i.e. SLR data to LAGEOS prior to 1992. ITRF2000 contained that data, while ITRF2005 does not, due to its tight and firm release schedule. We have generated a TRF that includes the data obtained from LAGEOS since 1976. A comparison of this TRF to a similar one that does not include that data and spans exactly the same period with ITRF2005, should give some idea of whether the missing data contribute to the z-axis secular evolution or the scale difference observed between the SLR and VLBI contributions to ITRF2005.

The effect of the "missing" historical SLR data on the SLR-definition of the scale

To test whether the addition of the "historical" LAGEOS data (1976 to 1992) to the definition of the TRF would eliminate the differences seen between the ITRF2000 and ITRF2005 realizations, we simply reduced that data and added them to the 1993 – 2005 data, generating a new TRF and comparing that through a 14-parameter similarity transformation to the two realizations, ITRF2000 and ITRF2005. The results are tabulated in Table 2.

Our solution is identical to neither ITRF2000 nor ITRF2005, although very close to both. This is expected of course since this is a SLR-only TRF and not a combination product with input from other techniques. Examining the differences in the scale and its rate, we notice that in the case of ITRF2000, our TRF indicates the same level of disagreement as it was originally seen between the SLR-only contributed inputs to this model. Similarly, we see the same for ITRF2005, and the combined difference is exactly what is seen when comparing one ITRF to the other. The fact that a TRF that contains the historical LAGEOS data shows similar differences to the ITRF2005 as does the one without that data, indicates strongly that the lack of that data cannot be the main reason of the observed differences.

***Table 2**. Similarity transformation parameters between SSC (JCET) L 06 and ITRF realizations.*

Parameter	**SSC (JCET) L 06.97 vs. ITRF2000**	**SSC (JCET) L 06.97 vs. ITRF2005**
D_x	-8.82 +/- 1.02 [mm]	1.25 +/- 0.91 [mm]
D_y	3.21 +/- 1.01 [mm]	8.37 +/- 0.91 [mm]
D_z	-5.65 +/- 0.95 [mm]	-6.59 +/- 0.86 [mm]
D_s	**0.52 +/- 0.15 [ppb]**	**-0.87 +/- 0.13 [ppb]**
R_x	-0.24 +/- 0.04 [mas]	0.05 +/- 0.04 [mas]
R_y	0.06 +/- 0.04 [mas]	-0.07 +/- 0.04 [mas]
R_z	0.15 +/- 0.03 [mas]	0.32 +/- 0.03 [mas]
$D_{x\text{-dot}}$	0.75 +/- 0.95 [mm/y]	-1.22 +/- 0.85 [mm/y]
$D_{y\text{-dot}}$	0.56 +/- 0.94 [mm/y]	1.37 +/- 0.85 [mm/y]
$D_{z\text{-dot}}$	3.10 +/- 0.73 [mm/y]	1.89 +/- 0.65 [mm/y]
$D_{s\text{-dot}}$	**-0.10 +/- 0.14 [ppb/y]**	**0.05 +/- 0.12 [ppb/y]**
$R_{x\text{-dot}}$	0.12 +/- 0.03 [mas/y]	0.12 +/- 0.03 [mas/y]
$R_{y\text{-dot}}$	-0.02 +/- 0.03 [mas/y]	0.02 +/- 0.03 [mas/y]
$R_{z\text{-dot}}$	0.02 +/- 0.03 [mas/y]	0.01 +/- 0.03 [mas/y]

In addition to the ‘geometric’ test of the scale implied by different spans of SLR data, we have also examined the dynamic definition of the scale, through the estimation of the GM_E constant from the different data sets. The SLR technique obtains the definition of the scale from the adopted speed of light in vacuum, v_c, however, because it involves satellite orbits, this scale should also be consistent with the size of the orbit as it is constrained by Kepler’s third law. With v_c fixed, we can monitor any changes in the intrinsic SLR scale through the estimation of GM_E. The historical data were reduced in three different ways (arc-lengths), in order to verify that this is also not a factor in the development of the TRF: fortnightly (F), monthly (M), and quarterly (Q) arcs. With each expansion of the arc-length, any unaccounted systematic errors in the description of the site-motions is smoothed out by averaging, since more data from other, non-affected sites contribute to the definition of the TRF over that interval of time. Table 3 indicates that a comparison of the GM_E estimates from these solutions to the value that we obtain from the weekly-arc (W) analysis for the 1993- 2005 period, shows no systematic difference, and certainly no scale change larger than the calibrated uncertainty of the estimates.

***Table 3**. GM_E estimates from two SLR data spans: 1993 – 2005 and 1976 – 2005.*

Source of displayed GME	**Value of GME**
IERS Conventions 2003	398600.441500 x 10^9 [m^3/s^2]
SSC (JCET) L 06 W 1993 - 2005	398600.441659 x 10^9 [m^3/s^2]
SSC (JCET) L 06 F 1976 - 2005	398600.441634 x 10^9 [m^3/s^2]
SSC (JCET) L 06 M 1976 - 2005	398600.441633 x 10^9 [m^3/s^2]
SSC (JCET) L 06 Q 1976 - 2005	398600.441633 x 10^9 [m^3/s^2]

We can reach two main conclusions from the above table: (a) the effect of the historical data in the intrinsic definition of the scale in SLR is at most at the level of 0.1 ppb, and (b) the effect of the arc-length used in the reduction of the data on the scale is even less significant, less than 0.002 ppb. A calibrated estimate of the accuracy of these estimates at the 99% level of confidence is 0.2 ppb or approximately 1.3 mm.

Subset solution results

We investigated the effect of the "evolution of the network" with the development of a number of TRFs from independent sub-sets of the data in various combinations (Figure 2). With only some thirteen years of data to work with, we went as far as ¼ of the data, i.e. the smallest set of data spanned just over three years. This seemed to be marginally acceptable for a quality TRF, with six years being a comfortable minimum for a robust TRF product (specially for velocity estimates). We have two strategies in forming these subsets: (i) using similar amounts of data spanning the same period of time, and (ii) using the same amounts of data sampling totally different time periods. In the first case for example, we used ¼ of the data to generate four different TRFs, each based on the weeks that span the same time-period, every subset formed by choosing every 4th week from the ensemble of all weeks available. In the second case, we also have four TRFs formed on the basis of approximately ¼ the total data, but in this case we broke up the total interval in four equal-length intervals, so each TRFs is fit to data from a different period of time (and a different network with different conditions and performance).

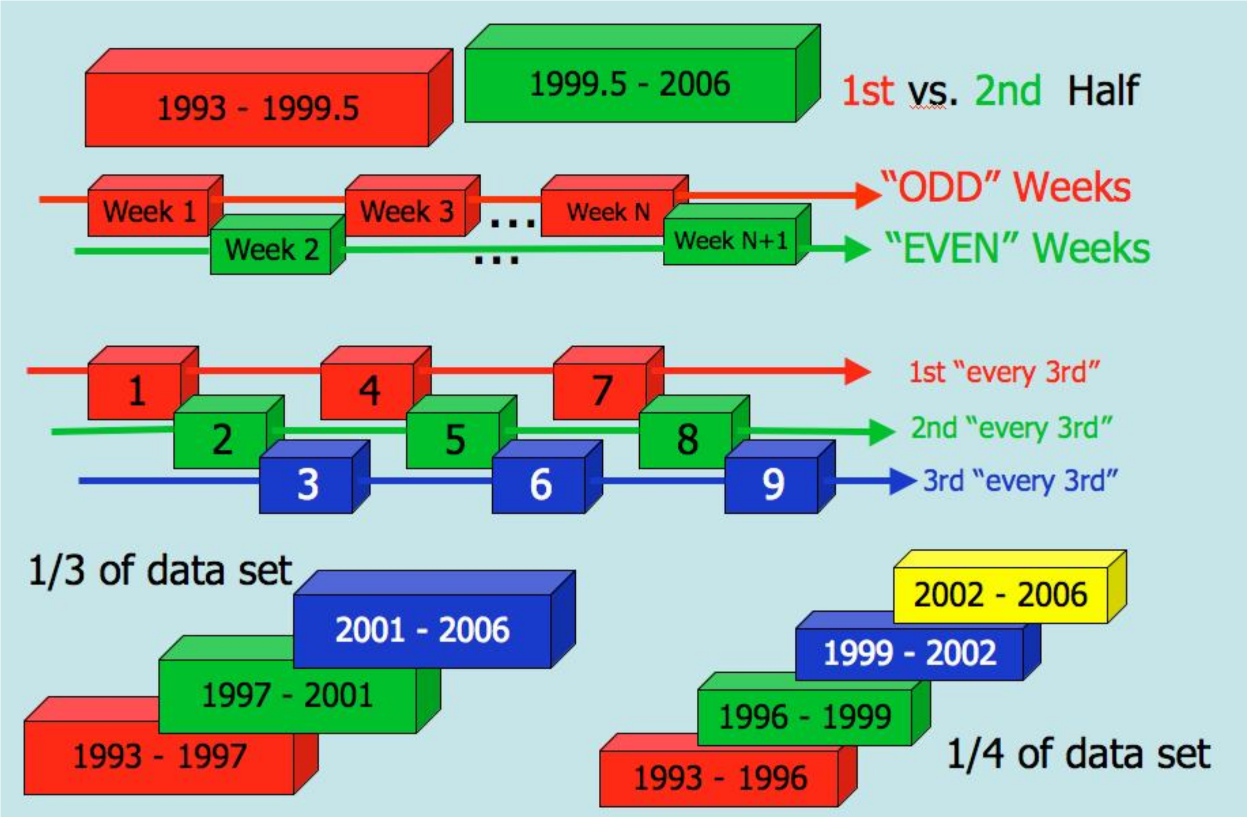

***Figure 2**. The four groups of subset solutions used in this investigation*

Case	ΔX [mm]	$\sigma_{\Delta X}$ [mm]	ΔY [mm]	$\sigma_{\Delta Y}$ [mm]	ΔZ [mm]	$\sigma_{\Delta Z}$ [mm]	3D |Δ| mm	$\sigma_{3D\Delta}$ mm
3 **Odd**	-8.37	±10.91	19.25	±10.78	-4.20	±10.32	**21**	**± 17**
4 **Even**	-12.62	± 8.93	5.15	± 8.82	-12.50	± 8.44	**18**	**± 16**
5 **@ 3rd**	-7.92	± 18.84	-3.87	±18.61	3.56	±17.82	**10**	**± 31**
6	-7.61	± 8.66	19.78	± 8.56	-15.33	± 8.19	**26**	**± 16**
7	-11.36	± 10.41	9.03	±10.28	-11.58	± 9.84	**19**	**± 17**
8 **@ 4th**	-15.62	± 21.76	43.27	±21.49	16.57	±20.57	**49**	**± 36**
9	-17.75	± 18.87	16.31	±18.63	-29.03	±17.84	**38**	**± 33**
10	-6.61	± 17.18	-5.50	±16.97	-11.56	±16.24	**14**	**± 29**
11	-16.72	± 12.01	1.32	±11.86	-9.92	±11.36	**19**	**± 21**
1 **1/2**	-41.20	±35.82	6.26	±35.38	-10.10	±33.86	**43**	**± 61**
2	1.74	± 6.76	8.06	± 6.68	7.28	± 6.39	**11**	**± 11**
12 **1/3**	-49.10	± 22.39	52.74	±22.11	2.73	±21.16	**72**	**± 38**
13	-3.07	± 8.21	-13.72	± 8.11	5.90	± 7.76	**15**	**± 14**
14	-16.95	± 14.20	5.72	±14.06	4.28	±13.40	**18**	**± 24**
15 **1/4**	-60.49	± 23.68	57.43	±23.39	7.48	±22.39	**84**	**± 40**
16	18.65	± 31.40	-57.81	±30.88	-6.19	±29.50	**61**	**± 53**
17	-0.27	± 18.01	-4.74	±17.79	15.72	±17.03	**16**	**± 31**
18	2.07	± 12.29	7.16	±12.18	1.73	±11.60	**8**	**± 21**

Figure 3. *The four groups of subset solutions used in this investigation (top cases: same time-span, and bottom cases: disjoint time intervals).*

We will limit the discussion of our conclusions to two items of importance to the ITRF: the definition of its origin and its axial rate. The results are summarized in Fig. 3, in terms of the differences in each component Δx, Δy, and Δz, with respect to the solution obtained from the entire set of data. In order to facilitate their comparison we also formed a figure of merit, defined as the 3D positional difference, and formed as:

$\Delta = \sqrt{\Delta x^2 + \Delta y^2 + \Delta z^2}$.

We can draw several conclusions from this table:

- On average, each component is not determined to better than 6-8 mm (depends on time period)
- The 1993 to present data set is significantly non-uniform due to various factors
- There is a steady improvement over the years, however, we can see even 10-fold differences between different time-periods
- With the caveat that our calibrated error estimates are sufficiently realistic, and assuming that the second half of the 1993-2005 period is more representative of current network performance, we conclude that for a reliable definition of the origin of the TRF we need a data spanning more than ~6-7 years.

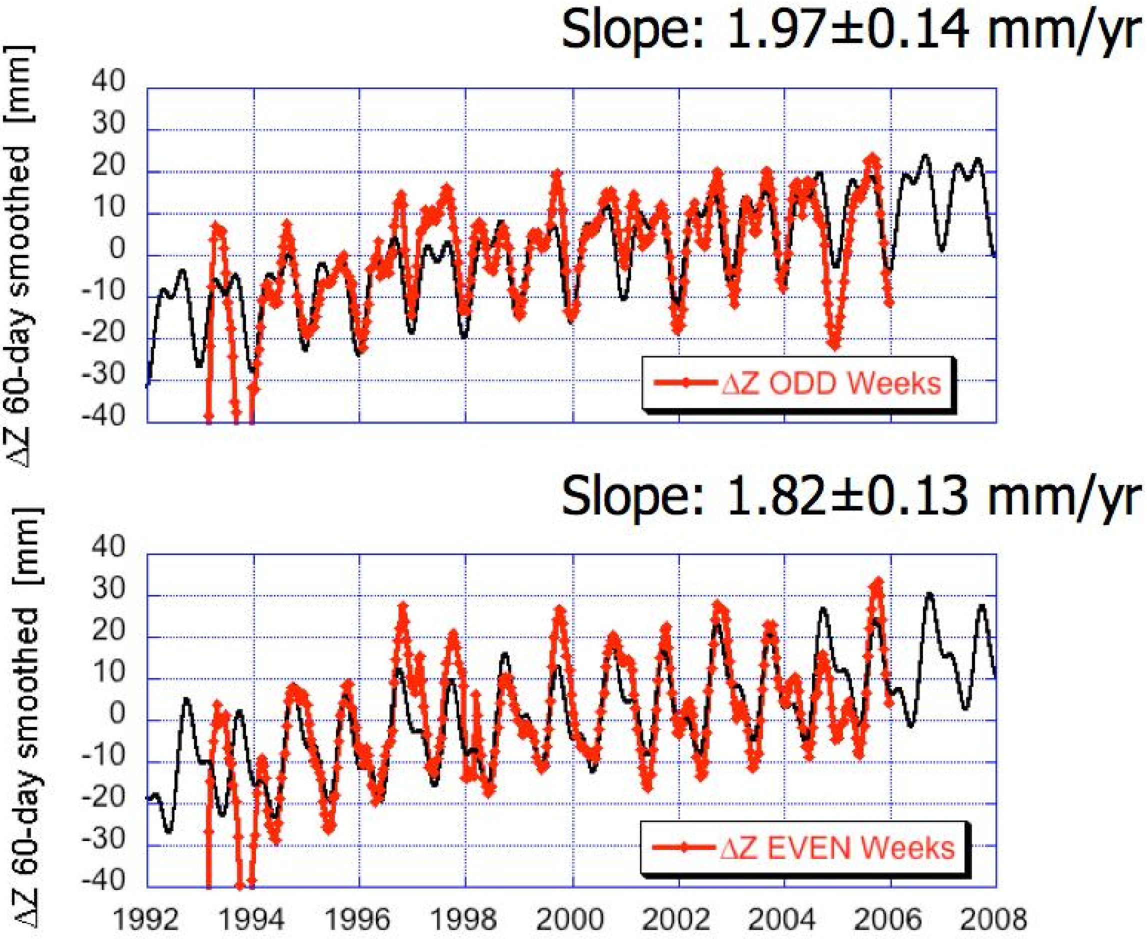

***Figure 4**. The time series of Δz (axial component of geocenter) from two independent subset solutions, each spanning the period 1993-2005.*

With each subset solution we also obtained a time series of the weekly variations of the origin with respect to the geocenter. These were analyzed in a similar manner to the origin components themselves, i.e., in comparison to the series we obtain from our ensemble solution that spans the entire time period. The axial component is the only one that shows a significant secular trend, so we will use that in our example. Figure 4 gives an example of the recovered series and their fit to a model that includes a linear trend and three periodic terms, for the two subsets formed from the selection of the “even” and “odd” weeks (i.e. every other week used). The two subsets span the same time period with just one week “offset”, but each set has about half the data of the entire data set. It is apparent from these two cases that the secular trend recovered here is statistically insignificantly different from what we obtained from the entire data set (cf. ~1.7 ± 0.1 mm/y). There are differences though in the periodic components’ (not magnitude) and when we compare the results from subsets that span even smaller spans of data (less than half), then even the secular trend is not recovered correctly (sometimes we even get sign-reversals!). These observations lead us to the following conclusions:

- Secular trends from same size data span agree to 7-10%
- Secular trends from spans smaller than ~7 years and different periods of time can differ up to 100%, indicating a highly non-stable network (shape, performance or a combination of both)
- The magnitude of the seasonal variations is stable when recovered from various subsets of the entire data set, but the phases seem to be sensitive to

that choice

- For the robust definition of secular trends and seasonal variations simultaneously, it is recommended that more than a decade of data (preferably from a stable network) be used.

Summary and future plans

This study investigated the robustness of the definition of the origin and scale of the TRF from SLR data (only) and with the LAGEOS and LAGEOS 2 data available over the period 1993 to 2005. The conclusions we reached are that these data define the origin at epoch to no better than 10 mm. The monitoring of the secular motion of the origin depends strongly on the network evolution and its performance. For a robust estimate of temporal variations of the geocenter we need data sets that span a decade or more, with a stable network. In such cases, the secular trends can be estimated with an accuracy of about 10%.

For a complete rationalization of the observed error signatures and the performance of future networks, we need a set of very carefully controlled simulations (underway). Extension of this simulation to include the other techniques will give us the advantage to "negotiate" trade-offs between the techniques, since they all act in a complementary manner in the definition of the ITRF. This will allow better use of the available resources and full exploitation of the benefits from each technique.

References

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