Geocenter Motion: Causes and Modeling Approaches

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Abstract

Since the first realization of the International Terrestrial Reference Frame (ITRF), its origin, defined to coincide with the geocenter, has been realized through the estimated coordinates of its defining set of positions and velocities at epoch. Satellite Laser Ranging (SLR) contributes to the ITRF realization this unique information along with that for its absolute scale, for over two decades. Over the past decade, the focus extended beyond the accuracy at epoch to include the stability of these realizations, given the increasingly more accurate observations of geophysical mass redistribution within the Earth system. Driven by numerous geophysical processes, the continuous mass redistribution within the Earth system causes concomitant changes in the long-wavelength terrestrial gravity field that result in geometric changes in the figure described by the tracking station network. The newly adopted ITRF development approach allows the simultaneous estimation of origin variations at weekly intervals through a geometric approach during the stacking step, and for the first time in the history of the ITRF accounts to some extent for these effects. Our dynamic approach has been used since the mid-90s, delivering, initially biweekly and later on, weekly variations of an "origin-to-geocenter" vector, simultaneously with an SLR-only TRF realization. Over the past year, the International Laser Ranging Service's (ILRS) Analysis Working Group adopted significant modeling improvements for the SLR data reduction of future as well as the historical SLR data. Based on this new standards, ILRS has embarked on a reanalysis of the LAGEOS 1 & 2 SLR data set up to present, to develop a uniformly consistent set of weekly variations with respect to a frame realized simultaneously by the ensemble of the data, closely approximating the current (scaled) ITRF2005. These series can complement the precise application of the ITRF when used as Cartesian offsets or the GRACE-derived monthly gravitational models, when converted to degree-1 harmonics. A simple model based on the dominant frequencies decomposition of the series can be easily used to account for the most significant part of the signal in various applications (examples).

Introduction

The origin of the Terrestrial Reference System (TRF) is realized through the adopted coordinates of its defining set of positions and velocities at epoch, constituting the conventional Terrestrial Reference Frame. Since many decades now, these coordinates are determined with space geodetic techniques, in terms of absolute or relative positions of the sites and their linear motions. Satellite tracking techniques use dynamics to define the origin and scale of the tracking station network since satellites "fall" naturally towards the center of mass of the central body and the size of their orbit is governed by the total mass of that central body. Today, late 2008, the state of the art TRF is the International Terrestrial Reference Frame (ITRF) with the latest realization being that of 2005—ITRF2005, [Altamimi et al., 2007]. An international and multi-technique effort is underway though to update this realization with a new one in late 2009, the ITRF2008 realization. This contribution focuses on the "origin to geocenter" vector variations and how these are monitored from the SLR network. We will examine first some theoretical estimates of the order of magnitude of expected variations and their nature, followed by examples of the recently determined series from SLR data, and we will conclude with examples of how their incorporation in the interpretation of geophysical signals leads to improved results.

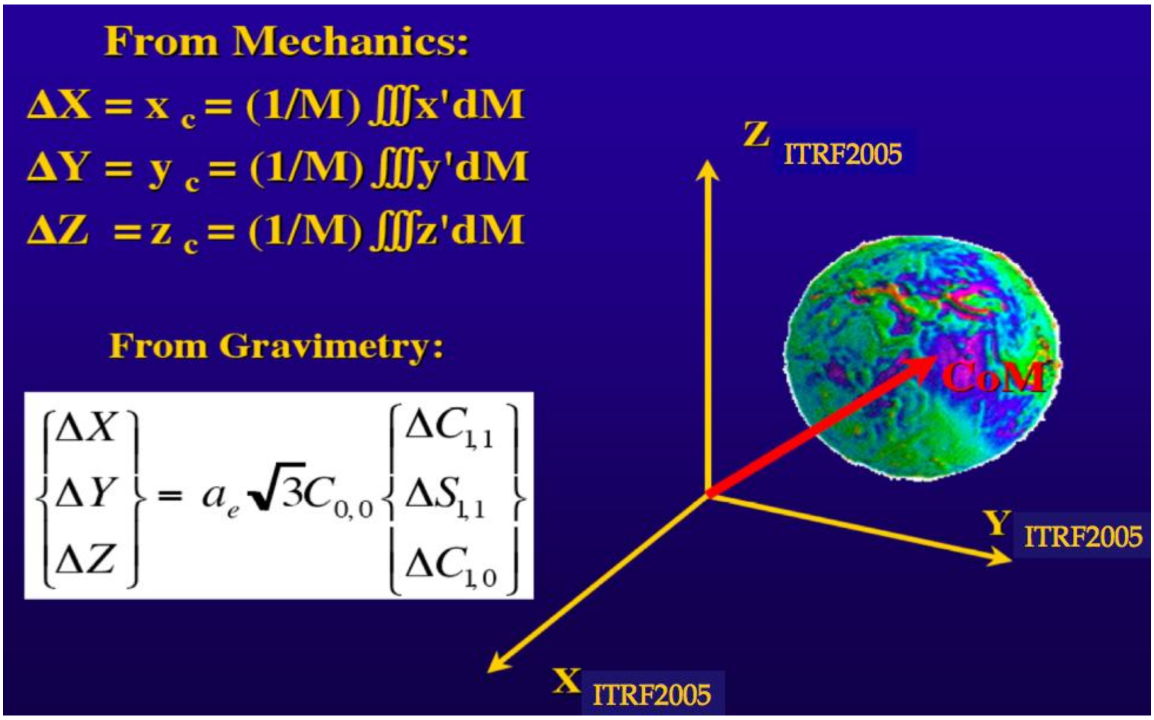

Figure 1. Center-of-mass (geocenter) definition and its relationship to gravity.

Temporal Gravitational Variations (TVG)

Despite the early use of space geodesy to develop accurate models of the terrestrial gravitational field, for many decades the field was viewed primarily as static, apart from the well known tidal variations. It soon became apparent that if not throughout its spectrum, at least the long wavelength part was exhibiting changes in time, because of reasons that were quickly traced to geophysical processes [Yoder et al., 1983]. Theoretical studies that followed over the coming years predicted further changes due to the redistribution of masses within the individual components of system Earth: atmosphere, oceans and solid Earth. This opened up an entirely new research area, temporal gravitational variations (TGV), and with it, it provided the missing link between space geodesy and climate change. As a result, it was widely accepted that since the "change" in climate change meant temporal change, the problem could not be properly addressed without a good handle on temporally changing gravitational signals with respect to a stable, well defined, and very accurate reference frame. Our focus here is in the degree-one terms that describe the non-geocentricity of the frame (Fig.1), with our primary concern being long-term, secular stability for that frame. Table 1 provides order of magnitude estimates of the plausible geophysical process that could contribute a secular component in the otherwise stable geocenter, with reference to the solid Earth component of the system.

Table 1. Plausible causes of secular geocenter change with expected order of magnitude.

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

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

Seasonal changes in the long wavelength harmonic coefficients of the gravitational potential have been closely correlated with mass transfer in the atmosphere, hydrosphere and oceans, from independent observations of other than SLR techniques and different space missions. Gravity-mapping missions, (e.g. GRACE), and to a lesser extent the future mission GOCE, address temporal changes directly from the gravimetric point of view. For the very low degree and order terms though, there is also a geometric effect on the origin between the instantaneous and the mean (over very long time periods) reference frame as shown in Figure 1. This is one of the “couplings” between satellite dynamics and Earth geophysics and geokinematics.

SLR contribution to the Terrestrial Reference Frame

SLR has been for decades a primary tool in the establishment and maintenance of the TRF and monitoring of Earth’s Orientation Parameters (EOP), in addition to being an extremely simple, precise and failsafe tracking technique. SLR data contributed in this effort the most accurate results yet, demonstrating early enough millimeter-level accuracy for short-term averages for these quantities [Pavlis, 1999, 2002]. Other satellite techniques, like GPS and DORIS, can potentially contribute to the definition of these quantities, however, due to the nature of these techniques, their contribution is limited in accuracy due to confounding with other parameters. SLR can determine a “SLR-realization” of the TRF at present on a weekly basis with accuracy at the centimeter level. These weekly series are “stacked” over time, and subsequently, combined with the contributions from other space techniques, they produce the new, global TRF. This process was first used in the development of ITRF2005 [Altamimi et al., 2007] and will be followed also in the development of the new TRF realization “ITRF2008”, due sometime in 2009.

Although the SLR ground network of prime contributing sites has evolved considerably over these years, it still remains very poor in its global coverage, with a profound imbalance between north and south hemisphere stations (Fig. 2). It also suffers from long outages at sites that cease operations for extended time periods for upgrades or other reasons, due to redundancy gaps over certain areas. Finally, as [Angermann and Müller, 2008] point out, an examination of the 1993 to 2007 data set from the two LAGEOS targets that almost exclusively support the ITRF development, indicates that in addition to the geometric imbalance of the two hemispheres there is also a huge imbalance in terms of contributions between southern hemisphere sites. In particular, the two sites in Australia are responsible for almost all of the data collected in the southern hemisphere. These issues have a direct impact on the development of a stable TRF and they are being addressed now in studies for an improved network of space geodetic techniques that will replace the currently operating ones, with an emphasis on multi-technique co-locations and uniform global distribution [Pavlis and Kuźmicz-Cieślak, these proceedings].

Figure 2. The ILRS network of stations with the most productive stations highlighted in ellipses and the lopsided nature of the network indicated by the large difference of sites between the north and south hemispheres. The loss of Tahiti over a significant time period created also a huge gap in longitude (~135°) in the southern Pacific region.

In preparation for the new ITRF2008, all of the LAGEOS and LAGEOS2 data are being reanalyzed by the ILRS Analysis Centers (AC), using improved modeling of biases, spacecraft dynamics and geometry, and background models. This time around the ILRS has extended the analysis to include the majority of the "historical" LAGEOS data, prior to 1993, starting with 1983. The extension to 1983 and not all the way back to the launch of LAGEOS, May of 1976, was decided after preliminary analyses indicated that the data prior to 1983 were not of the quality required for the definition of the TRF, suffering from large and unstable biases and poor network geometry. From the preliminary analyses at the JCET/GSFC AC, the evolution of the geocenter compared to the a priori definition from the underlying SLRF2005 TRF (compatible with ITRF2005S, but extended to apply to the period 1983 to 1993), seems very stable, indicating no significant secular variations as the prior models did with respect to ITRF2000, and with a clear annual signal. These preliminary series are displayed in Figure 3 for the recent period 1993 to end of 2008, when the resolution of the series is at weekly intervals. Note the lack of secular trends in the series. The years before 1993 do not support such a resolution and the official ILRS contribution is provided in 15-day averages. These series are obtained from a multi-year solution for a SLR-only TRF in the form of a set of coordinates at a fixed epoch (2000.0) and associated linear velocities. During the solution, we are determining weekly offsets of the frame determined with each weekly data set from the mean frame that is determined by the ensemble of the data. This approach delivers a consistent frame and geocenter series and it is applicable for a sequential approach of augmenting an established TRF with additional data as they are collected in time, to extend its validity without changing its definition.

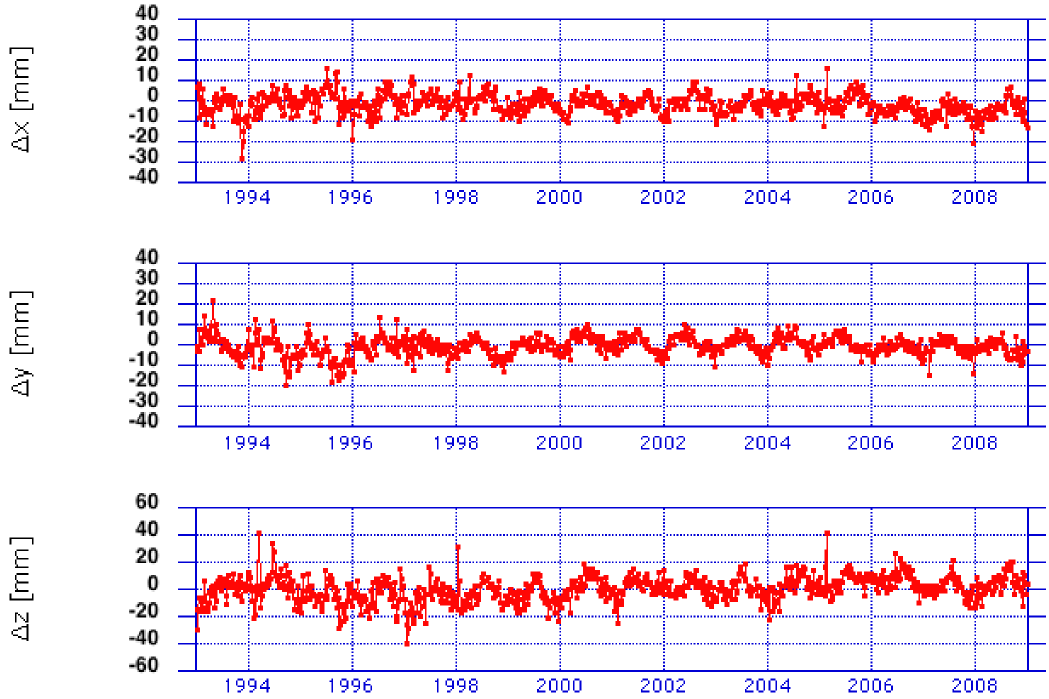

Figure 3. The new SSC(JCET) L 08 geocenter series based on SLRF2005 a priori and improved modeling of the LAGEOS SLR data.

Since the ITRF is not a SLR-only affair, harmonizing the modeling standards and the analysis principles to those commonly accepted by all the other space geodesy services and sanctioned by the International Earth Rotation and Reference Systems Service (IERS), it is vital in the development of a high quality product. Our recent reanalysis enforced as a prerequisite of all contributing ACs to follow the presently adopted IERS Conventions and Standards 2003, [McCarthy and Petit, 2004]. We hope that similar strict enforcement of these standards by the other techniques will help avoid the problems that the community faced with the release of ITRF2005 due to the erroneous application of the pole tide correction by a number of VLBI ACs. The consistency amongst the ILRS AC preliminary submissions is perhaps a strong indication of the benefit one can expect from enforcement of these standards throughout the contributing services.

Network geometry and data quality impacts on the SLR TRF

We have already discussed the poor quality of the SLR network and hinted at the large changes that it has undergone over time, in terms of both system quality and spatial coverage. In an attempt to gauge the level of TRF accuracy that these "different" networks could support during the years of evolution, we have generated a number of variants of the SLR-only TRF with subsets of the data (Fig. 4).

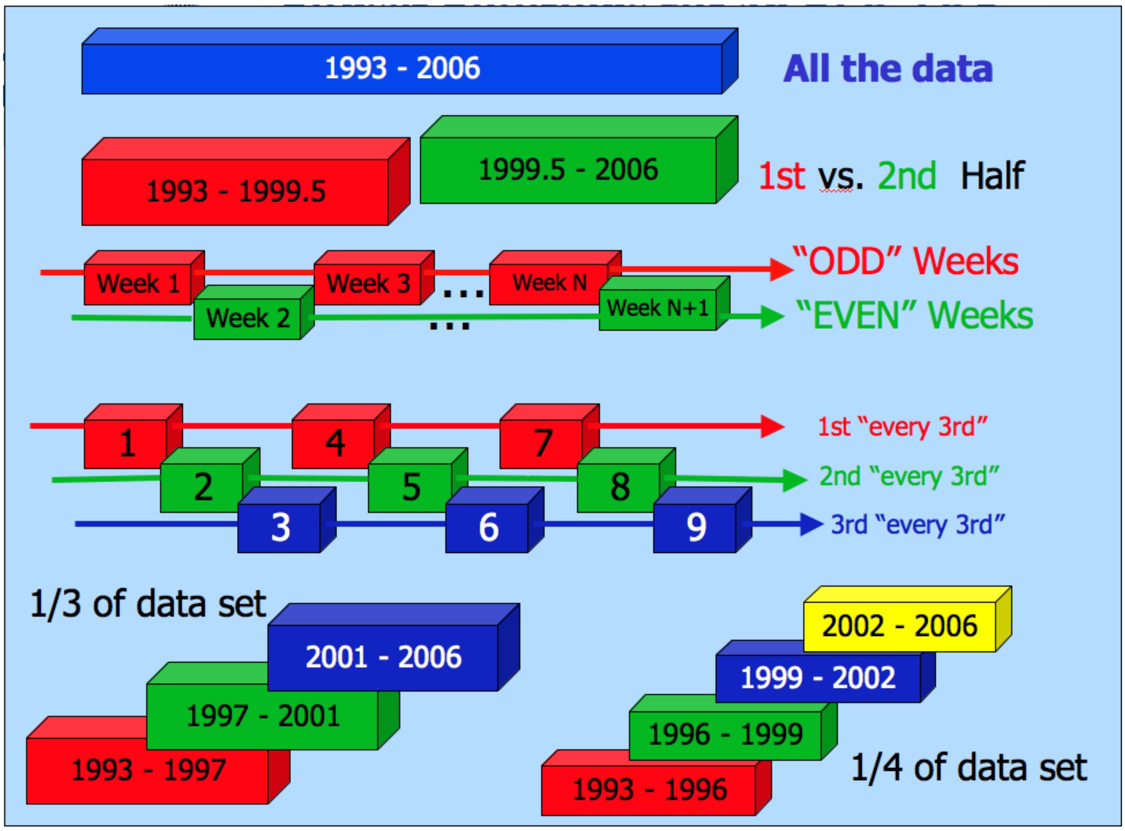

Figure 4. A graphical representation of input data variations for the development of a SLR-only TRF from subsets of the LAGEOS SLR data.

The idea behind these solutions is that the data set that is used in each case is strong enough to support the development of a TRF realization and if the data are of the same quality and represent the same geometry, then a comparison of the resulting TRF to the one obtained with the entire data set should give us some reasonable estimate of the relative accuracy between these variations. Accounting for the different number of observations between these solutions provides a good measure of the sought-for figure of merit for the variable accuracy of the geocenter definition in the 1993 to 2006 period. The tested variations were designed to provide information on the inherent strength in the data as a whole, as well as the evolution of this strength over the years, due to the evolution of the size, shape and technological advances of the ground network.

Solutions that spanned the same period of time, e.g. using the "odd-numbered" vs. "even-numbered" weeks (two different solutions), or picking every 3rd week (three different solutions), picking every 4th week (four different solutions), gave us a feeling of how much dependent are these solutions to the underlying data. Assuming that data obtained within one, two or three weeks apart should more or less contain the same information and they should thus yield the same TRF origin, the differences that we found between these realizations in terms of their origin with respect to that defined by the ensemble of the data gives a realistic estimate of how the technique can determine the origin of the TRF.

Table 2. Origin difference statistics between various subset SLR-only TRF realizations. All results are in [mm].

Case	ΔX	σ ΔX	ΔY	σ ΔY	ΔZ	σ ΔZ	3D |Δ|	σ 3D Δ
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**
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**
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**

On the other hand, decimating the data set in subsets over time, examines more the effect that the evolution of the network size, shape and hardware have on the resulting TRF. Some of the results of these TRF comparisons in the three origin components are shown in Table 2 by component, as well as a root sum square (RSS) of the three. Examining these results we can reach some conclusions on the present state-of-the-art:

- The TRF origin defined by SLR is accurate at no better than 10 mm at present;
- The first half of the data is of much less quality than the second, possibly by a factor of four or so;
- Finer breakdown of the data set (e.g. in four parts) reveals an even clearer trend in the quality of the data and the network, indicating that the very early years were as bad as ten times the later years, with a linear transition in between.

This fact along with the large secular trends that were observed between the last two ITRF realizations, cast serious doubts on the ability of current SLR to support the accuracy requirements set forth by GGOS and primarily driven by the need to monitor sea level change with an accuracy of 0.1 mm/y [Pavlis et al., 2008].

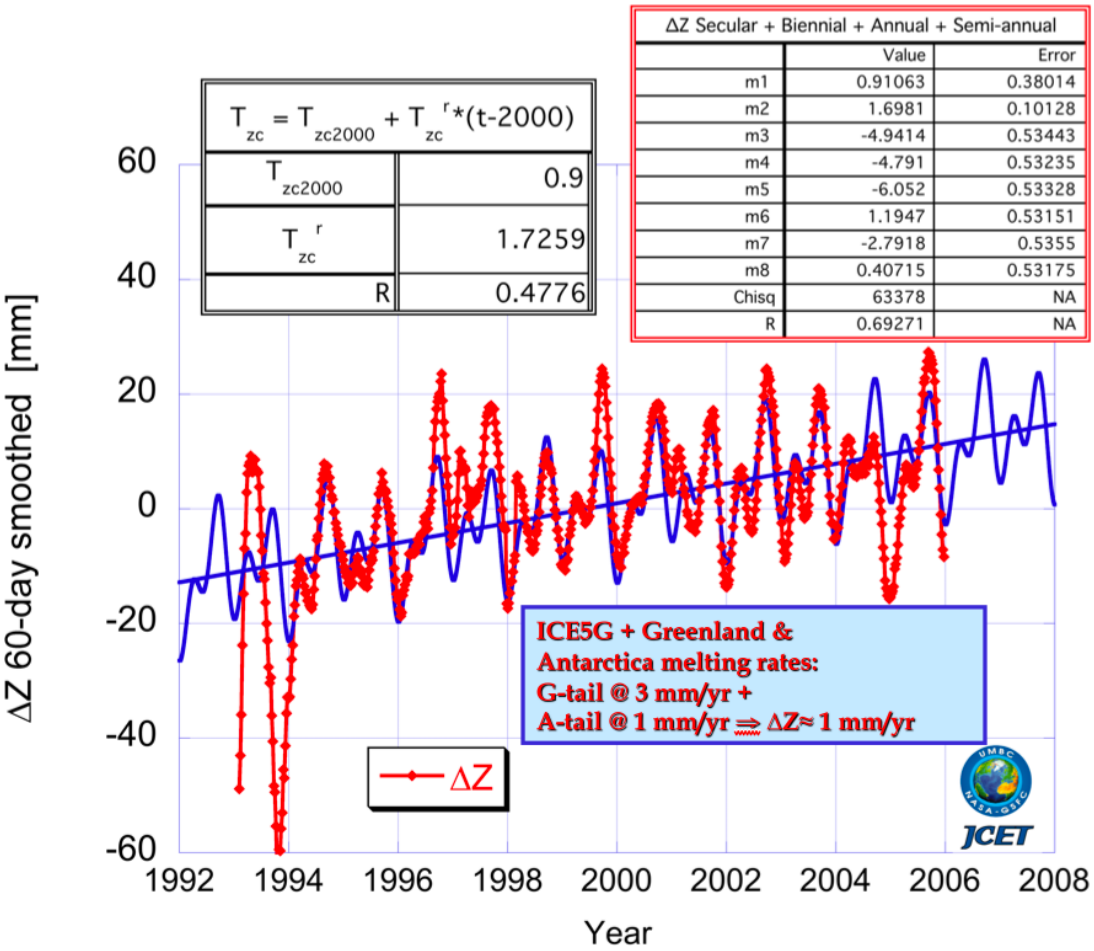

Figure 5. Variation of the Z-component of the geocenter from SLR, referenced to ITRF2000, from weekly solutions, smoothed with a 60-day boxcar filter. A four-component fit is also shown along with some estimates of plausible trends due to Greenland and Antarctica melting.

Applications of the SLR TRF and geocenter series

One of the most demanding in terms of accuracy geophysical investigations is monitoring mean sea level (MSL) variations over decades. The fact that it has huge societal implications makes this effort important and requires the utmost care in maintaining current estimates and understanding the processes that drive this change. The underlying TRF is terribly important because it relates estimates obtained from various oceanographic missions that can be decades apart, along with local, regional and global estimates from *in situ* data like tide gauges.

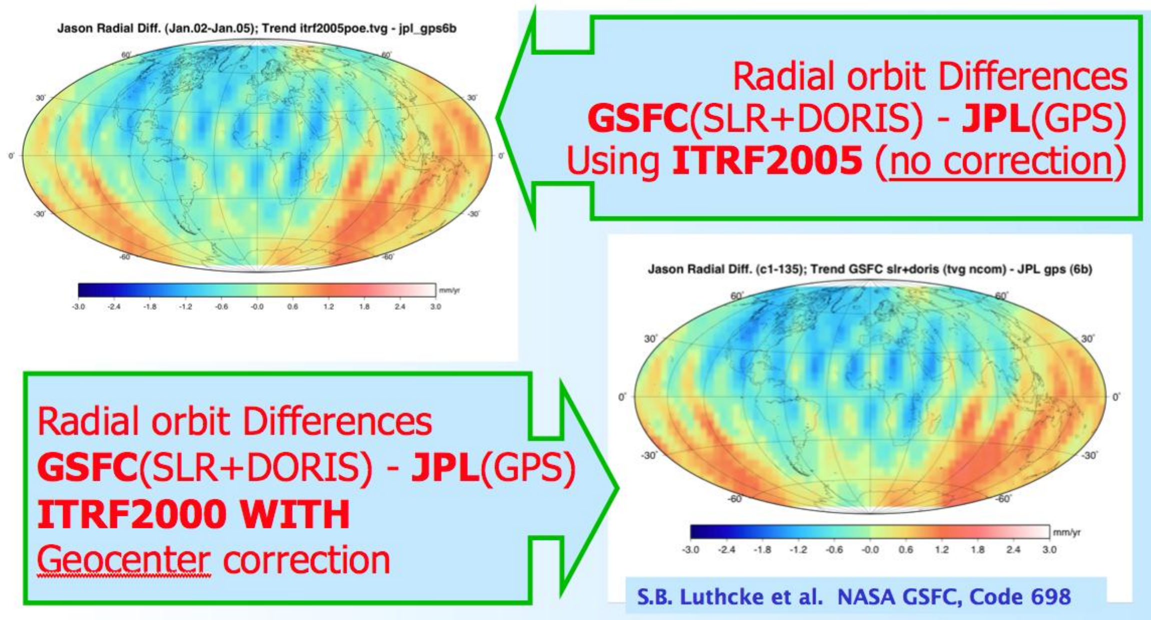

Figure 6. ΔMSL trends from JASON-2 observations (Jan. '02 – Jan. '05) reduced with ITRF2005 (left) and ITRF2000 plus the geocenter corrections shown in Figure 5. Both are differenced from JPL reductions that use GPS-based orbits with little dependence on dynamics (nearly geometric solutions).

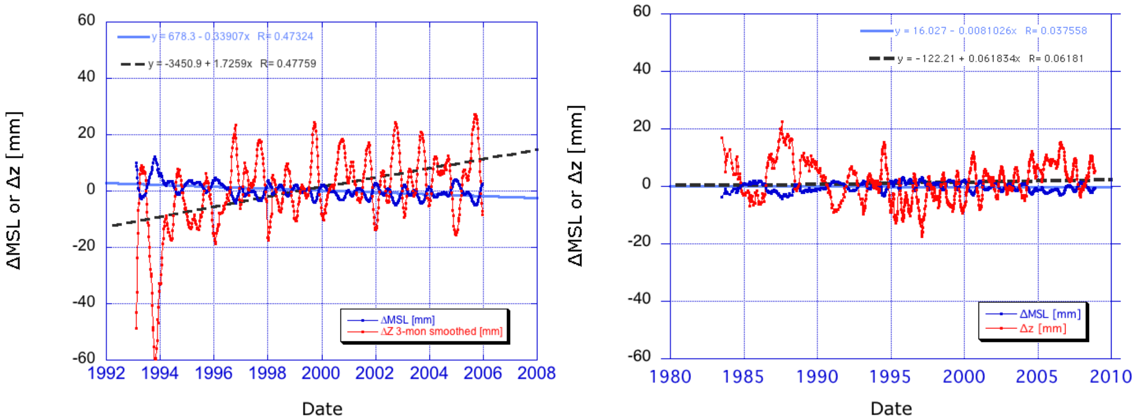

Figure 7. ΔZ_{COM}-induced trend in MSL for the new ITRF realization on the right and the past one on the left.

The application of the ITRF2000 had contaminated the observed trends of MSL due to the unstable origin definition, primarily the secular trend in the Z component that was clearly determined by SLR (Fig. 5). When the geocenter variation series was used in the reduction of the MSL data, the global picture that was obtained looked identical to that when the new ITRF2005 realization was used (Fig. 6), which had a much less prominent trend in the origin components. This was a clear indication that SLR was all along observing the correct geocenter, however, the construction of ITRF2000 was such that it could not account for it. The adoption of a new approach in the construction of the ITRF since the ITRF2005 realization has corrected the problem, as it can be verified by looking at Figure 7. The left figure shows the effect that the ITRF2000 vs. ITRF2005 Δz_{COM} has on the MSL trend, while the right side figure does the same between ITRF2005 and our preliminary version of a SLR-only ITRF2008. The linear fits to these "aliased" signals are 0.339 mm/y for the past realization and 0.008mm/y for the new one. Given the associated statistics for the MSL estimates (on the order of 0.1 – 0.3 mm/y), the former error is very significant, while the latter is clearly insignificant. Unfortunately, these are estimates over the period that is covered by data used in the construction of these ITRF realizations, so they are really not able to tell us how the new ITRF will perform in the future. The fact though that there is no significant trend over the past 25 years is rather reassuring for its future performance.

Summary

The establishment of the Terrestrial Reference Frame is a collective effort of many research institutions and all of the space geodetic techniques. Although many of the techniques share strengths and weaknesses, each technique has some unique role in this effort. Satellite Laser Ranging, one of the very first precise space geodetic techniques to contribute to this effort, uniquely defines the origin of the TRF and its temporal variations, and in part its scale and its variable orientation. As the development of the TRF over time improved, so did our ability to analyze SLR data, thereby contributing higher quality products for subsequent realizations. This presentation gave some examples of SLR contributions in the past (ITRF2000 and ITRF2005), and discussed with examples, the improvements in the analysis and modeling of SLR observations used in the development of a new realization of the TRF (ITRF2008). These few examples show clearly that the usual tag-war between science and technology is alive and well, and guarantees that our knowledge about Earth and its environment will continuously improve, as long as we continue to invest in these efforts.

Tracking-network origin definition varies from week to week due to geophysical fluid redistribution in the Earth system, ILRS however monitors these variations with mm-level accuracy, including linear rates. SLR network non-uniformity and varying data yield result in variable quality of the above results over the past decade. Future requirement of definition at epoch at < 1mm and rates of < 0.1mm/y are dictated by MSL change studies and they will need a revised network and analysis approach to meet consistently and over decades. Application of SLR monitoring of the "geocenter" in altimetry data reductions produces MSL results qualitatively equivalent to those derived from the newer and more correct ITRF realizations, demonstrating SLR's ability to accurately monitor such variations.

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