SLR CONTRIBUTIONS IN THE ESTABLISHMENT OF THE TERRESTRIAL REFERENCE FRAME

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Abstract

The origin of the Terrestrial Reference System (TRS) is realized through the adopted coordinates of its defining set of positions and velocities at epoch, constituting the conventional Terrestrial Reference Frame (TRF). Since over two decades now, these coordinates are determined through space geodetic techniques, in terms of absolute or relative positions of the sites and their linear motions. The continuous redistribution of mass within the Earth system causes concomitant changes in the Stokes' coefficients describing the terrestrial gravity field. Seasonal changes in these coefficients have been closely correlated with mass transfer in the atmosphere, hydrosphere and the oceans. The new gravity-mapping missions, CHAMP and GRACE, and to a lesser extent the future mission GOCE, address these temporal changes from the gravimetric point of view. For the very low degree and order terms, there is also a geometric effect that manifests itself in ways that affect the origin and orientation relationship between the instantaneous and the mean reference frame. Satellite laser ranging (SLR) data to LAGEOS 1 and 2 contributed in this effort the most accurate results yet, demonstrating millimeter level accuracy for weekly averages. Other techniques, like GPS and DORIS, have also contributed and continue to improve their results with better modeling and more uniformly distributed (spatially and temporally) tracking data. We present our operational methodology and results from our latest analysis of several years of LAGEOS 1/2 and ETALON 1/2 SLR data, assess their accuracy and compare them to results from the various other techniques. A comparison of the SLR-derived trajectory of the "geocenter" with respect to the TRF, reveals a strong correlation with the recent geophysical events. The interpretation and comparison will benefit significantly from the future availability of geophysical series at higher temporal resolution and with more accurate content.

Introduction

Satellite Laser Ranging (SLR) has been for decades a primary tool in the establishment and maintenance of the Terrestrial Reference Frame (TRF) and monitoring of Earth's Orientation Parameters (EOP), in addition to being an extremely simple, precise and failsafe tracking technique. In this brief review of the contributions of SLR in the development of the TRF, we present the results for ITRF2000 [Altamimi et al., 2001], where SLR defines directly the origin and in part (50%) the scale of the TRF, as well as some indirect contributions, such as the observation of geophysical signals, improvement of models, theoretical validations, etc., which also help develop a better TRF.

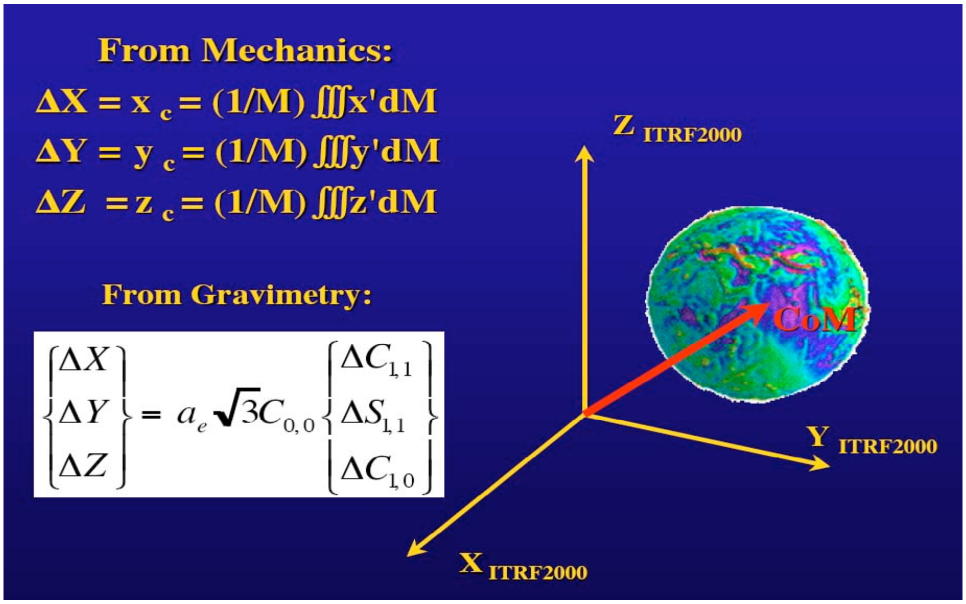


Figure 1. Center-of-mass (geocenter) definition and its relationship to gravity.

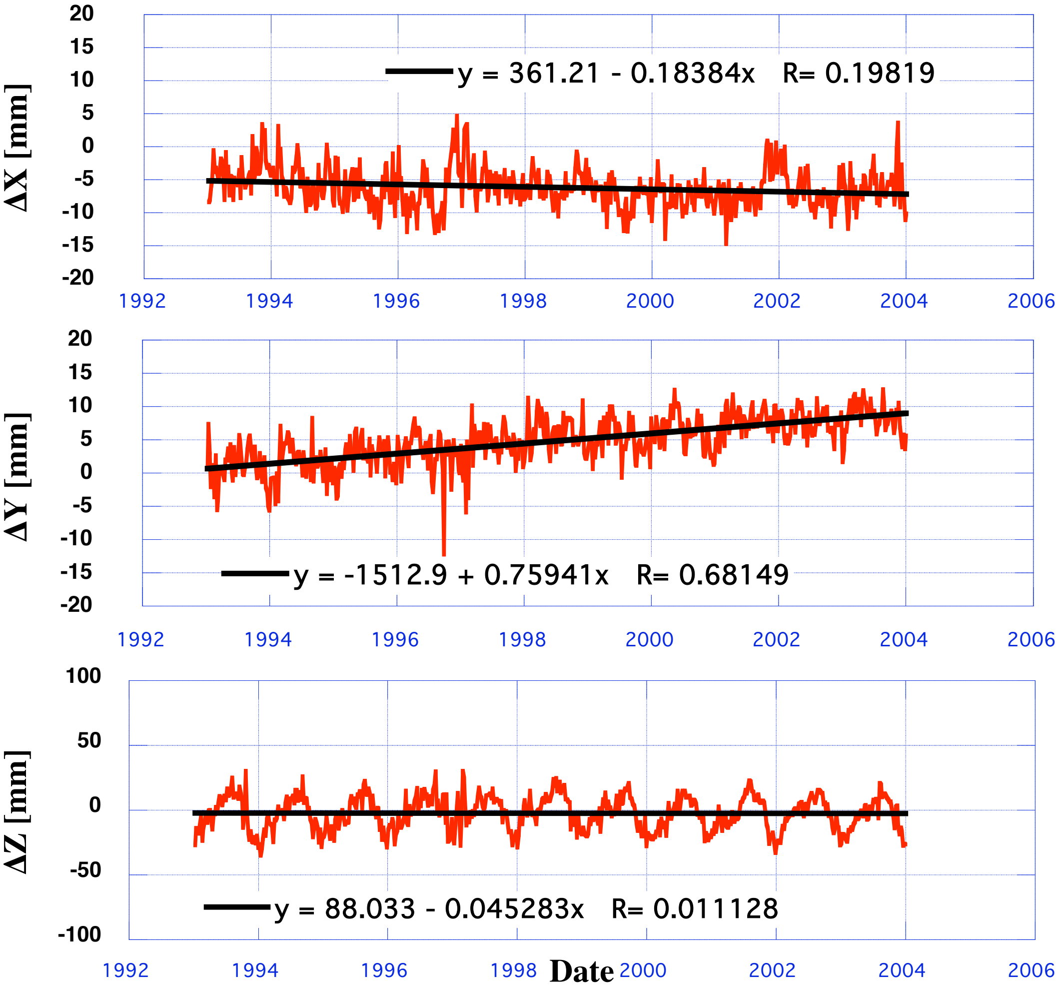
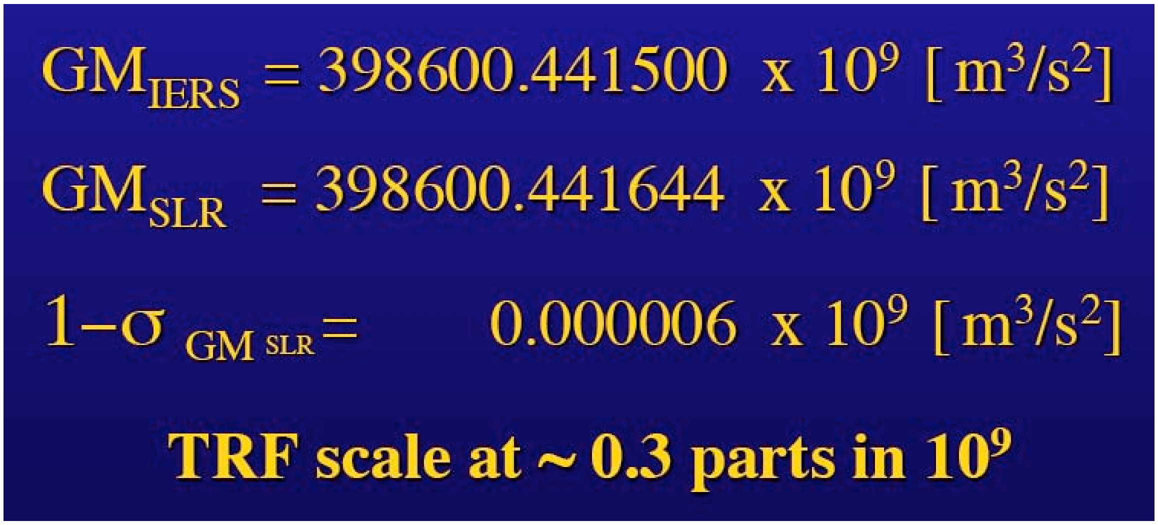


Figure 2. Center-of-mass (geocenter) variations at weekly intervals, SSC (JCET) L 2004.

Advances in technology require concomitant advances in science and vice versa. SLR has followed this principle for decades now, from the early (few-meter quality) systems to the latest (few-millimeter quality), highly automated and reduced size systems. At the same time, as scientists interpreted the higher quality results from SLR, the more interested they became and demanded even better quality data in order to reveal details that were possibly hidden in the higher level noise of the older systems. The technique reached maturity by the end of the ‘80s, however, it immediately entered a period of evolution which led to a wealth of major scientific contributions in several areas of terrestrial geophysics during the ‘90s: [Smith et al., 1990, 1994; Marsh et al., 1988, 1990; Degnan and Pavlis, 1994; Nerem et al., 1994; Pavlis, 1994; Lemoine et al., 1997].



$$GM_{IERS} = 398600.441500 \ \times 10^9 \ [\mathrm{m}^3/\mathrm{s}^2]$$

$$GM_{SLR} = 398600.441644 \ \times 10^9 \ [\mathrm{m}^3/\mathrm{s}^2]$$

$$1-\sigma_{\ GM\ SLR} = 0.000006 \ \times 10^9 \ [\mathrm{m}^3/\mathrm{s}^2]$$

TRF scale at ~ 0.3 parts in 10^9

Figure 3. Scale of the TRF from 11 years of weekly SLR arcs, SSC (JCET) L 2004.

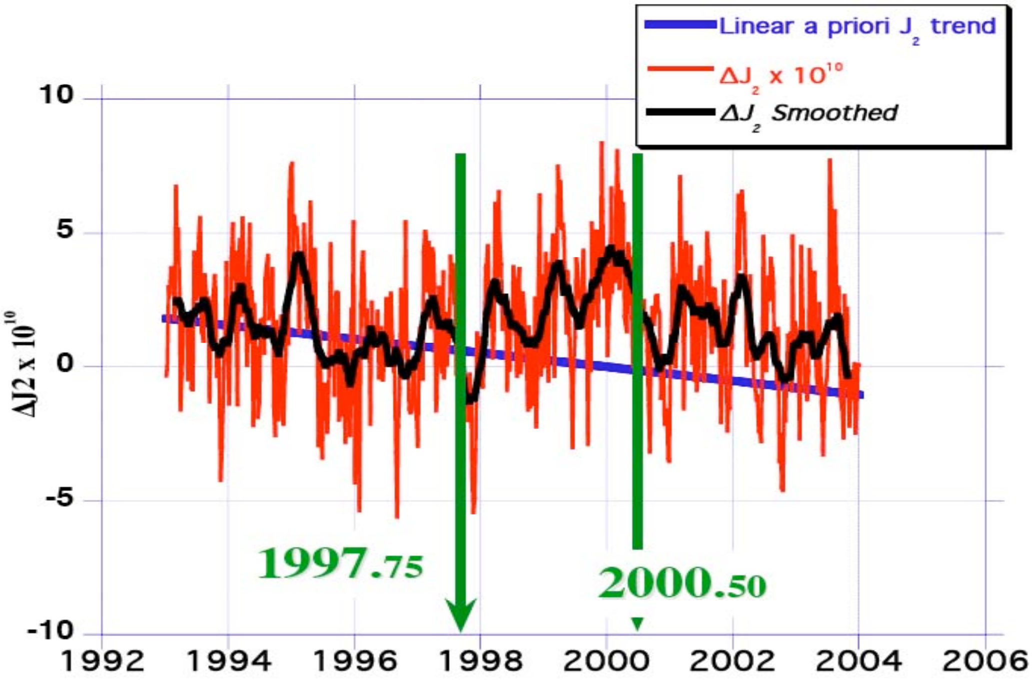


Figure 4. J_2 variation from eleven years of weekly SLR arcs, SSC (JCET) L 2004.

The design and manufacturing of smaller, more efficient, autonomously operated, yet more accurate systems, ushered us into the new millennium [Degnan, 2001; Nicolas et al., 2001]. This transformation was followed by a change in the scientific applications of the SLR technique. With newer technologies (e.g. GPS) taking on the crustal deformation and tectonic motion problem at a global scale, SLR has refocused on the areas where it contributes in an unique way and with the greatest impact for science: the definition of the TRF origin (Figure 1) and its temporal variations ("geocenter motion", Figure 2), the scale of the TRF (Figure 3), the precise determination of the long wavelength portion of the static and temporally varying part of the gravitational field of Earth (Figures 4-6), precise orbit determination (POD), the validation of radiometrically-determined orbits, the calibration of altimetric systems, exploitation of two-wavelength ranging for refraction modelling, tests of fundamental physics, interplanetary experiments, target characterization, orbital debris tracking, and several other areas.

In the following, we will highlight some of the recent achievements in the areas that are closely related to the development and maintenance of the TRF.

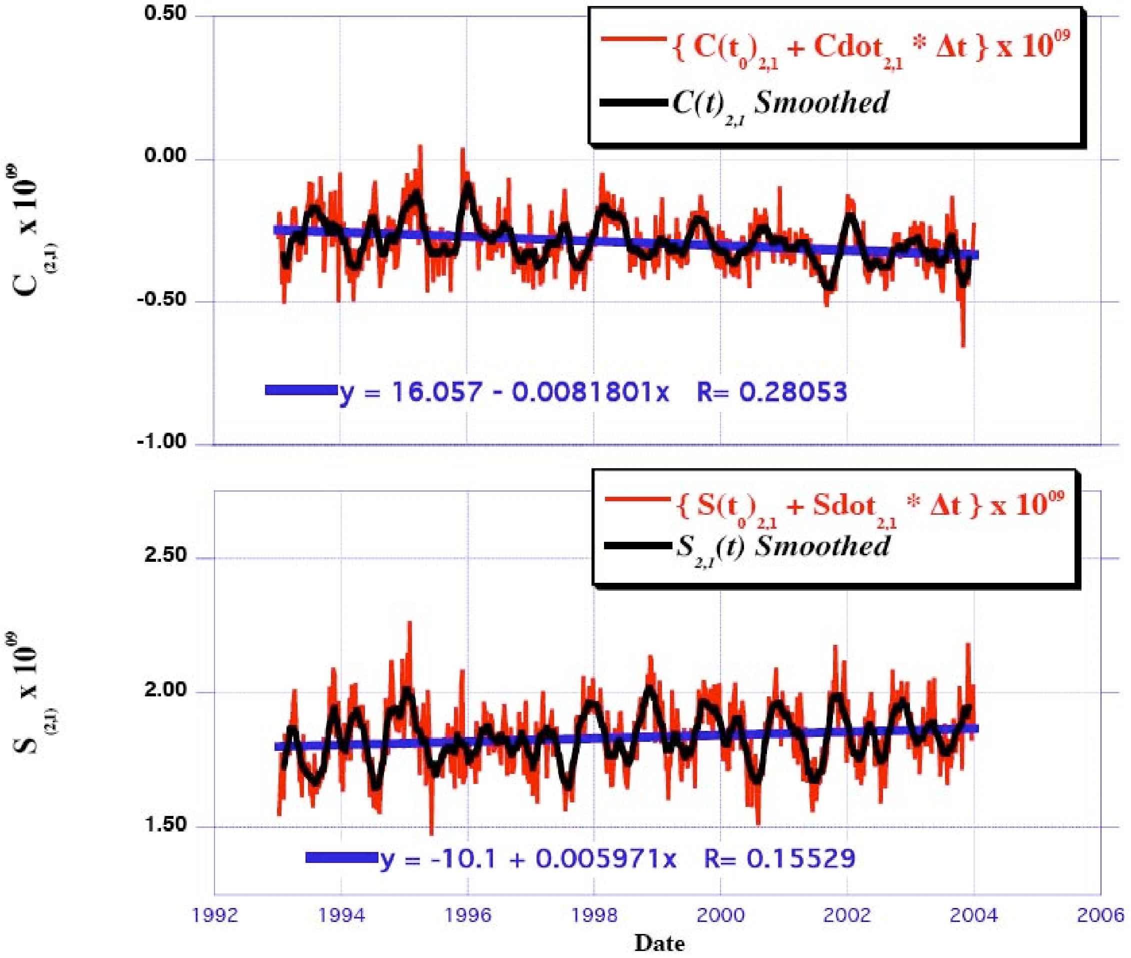


Figure 5. Axis of figure excitation from eleven years of weekly SLR arcs, SSC (JCET) L 2004.

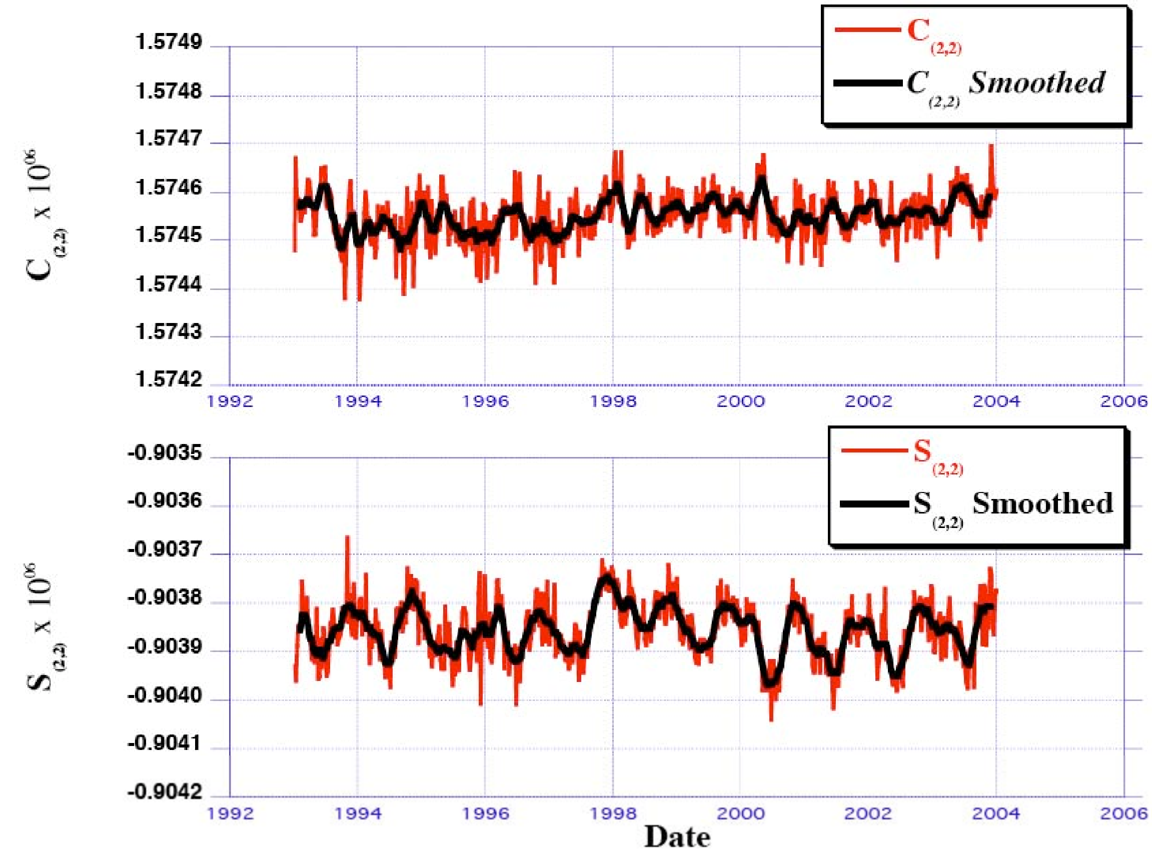


Figure 6. Dynamical equatorial flattening variation from eleven years of weekly SLR arcs, SSC (JCET) L 2004.

SLR and the Terrestrial Reference Frame

The origin of the Terrestrial Reference System 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 through space geodetic techniques, in terms of absolute or relative positions of the sites and their linear motions. In the early years ('60s) the use of optical tracking resulted in the first "global" networks and the establishment of crude (static) versions of the TRF with meter-level quality. These techniques were soon ('70s) followed by Doppler tracking with an order of magnitude improvement, only to be all displaced in the '80s by the early SLR and VLBI (Very Long Baseline Ineterferometry) systems that supported such groundbreaking international efforts as the two MERIT campaigns [Wilkins, 1981; Mueller, 1981] that launched the International Earth Rotation Service (IERS) which took over from the astrometry-based Bureau International de l'Heure (BIH). 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 (focus of the orbit) and the size their orbit is governed by the mass of that central body. This connection of the orbital dynamics with the properties of the central body led to the historical proposal for the use of artificial satellite dynamics for geodetic applications [Veis, 1960]. Today, the state of the art TRF is the International Terrestrial Reference Frame 2000—ITRF2000, [Altamimi et al., 2002]. An international and multi-technique effort is underway though to update this realization with a new one in early 2005, to be called ITRF2004.

For the first decades of space geodesy, the terrestrial system, apart from the well known tidal variations, was viewed as a static one. Even in these early days though, it soon became apparent that if not the entire system, some of its parameters were changing in time, and the reasons were quickly traced to geophysical processes [Yoder et al., 1983]. This was followed by theoretical studies predicting farther changes due to the redistribution of masses within the individual components of system Earth: atmosphere, oceans and solid Earth. This continuous redistribution of mass causes concomitant changes in the Stokes' coefficients describing the terrestrial gravity field. 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. This was fortuitous, since by this time the fortunes of the "big" and older space geodetic techniques (SLR and VLBI) were taken for the worse, with cutbacks and program reductions at national and international level. At the same time, it was widely realized that since the "change" in climate change meant temporal change, the problems 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. TGV thus became a new focus for the application of SLR to new problems and at the same time, a renewed role for SLR in the development of the TRF underlying the observed changes. This relationship was quickly identified as a "Catch-22", since to observe the changing world one needs a near-perfect TRF, which however is directly affected by these changes! Clearly only an iterative approach could give any results in practice.

We are thus in the early stages of this process, whereby the increased knowledge of System Earth allowed us to improve our definition of the TRF, which in turn allowed us to observe System Earth in a better way, learn even more about it, to be used to derive an improved TRF, and so on and so forth. Seasonal changes for example in the long wavelength harmonic coefficients of the gravitational potential have been closely correlated with mass transfer in the atmosphere, hydrosphere and the oceans, from independent observations of these Earth System components with other techniques and different space missions. The recently launched gravity-mapping missions, CHAMP and GRACE, and to a lesser extent the future mission GOCE, address these temporal changes directly from the gravimetric point of view. For the very low degree and order terms though, there is also a geometric effect that manifests itself in ways that affect the origin and orientation relationship between the instantaneous and the mean (over very long time periods) reference frame. This is one of the "couplings" between satellite dynamics and geophysics and geokinematics of Earth. 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, also contribute to the definition of these quantities, however, due to the nature of these techniques, their contribution is limited in accuracy. As these techniques continue to improve their results though, with better modeling and more uniformly distributed (spatially and temporally) tracking data, it is possible that they can become significant contributors in future TRF realizations. SLR can determine a “SLR-realization” of the TRF at present on a weekly basis with accuracy at the centimetre 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 is the proposed process to be followed in the development of the new TRF realization “ITRF2004”, sometime in 2005.

ITRF2000: The state-of-the-art in TRFs

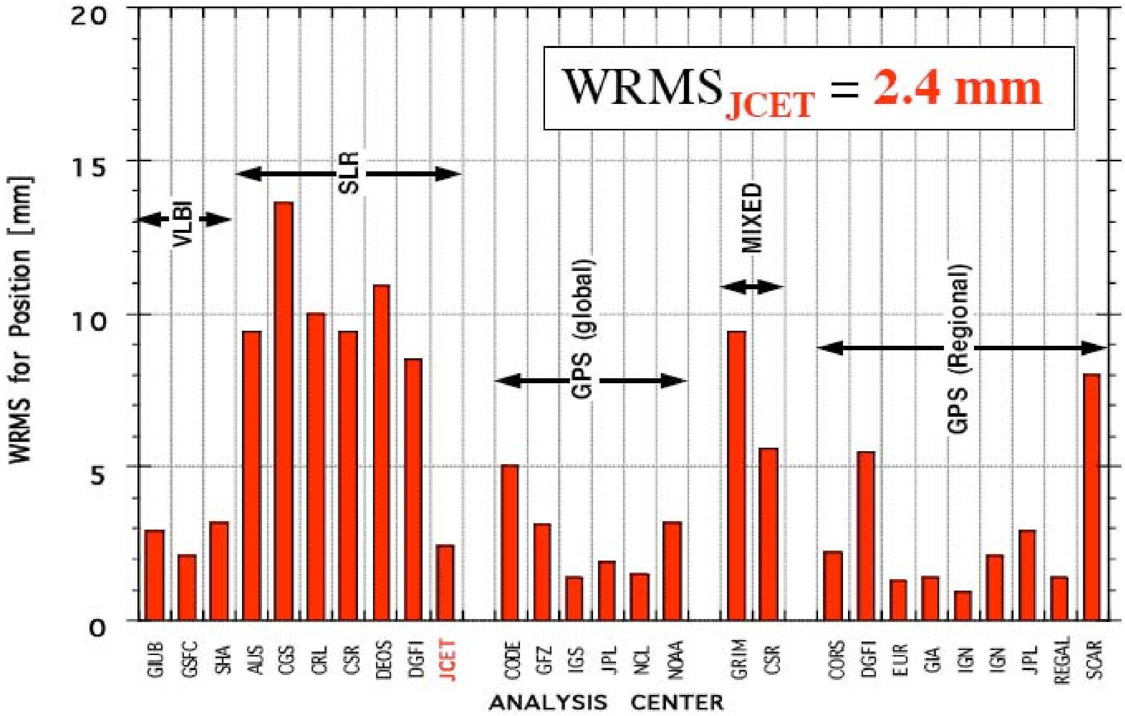


Figure 7. WRMS for positional components of individual ITRF2000 contributions.

The present state-of-the-art realization of the TRF is ITRF2000, as we already pointed out earlier. Here we will discuss the role of SLR contributions in its development and success. It should be pointed out that ITRF2000 was the first TRF that was developed based on a plan laid out ahead of its development and sanctioned by all techniques and analysis groups that eventually contributed to it. This was catalytic in that it engaged all analysis centers at all steps and through its evaluation over a couple of years and several dedicated meetings and workshops. During this process the value of organizing the Services for all geodetic techniques was recognized and this successful planning was used as the blueprint for the development of ITRF2004, with the individual contributions being channelled via the appropriate Services, thus ensuring uniformity, reliability and compatibility of the contributions.

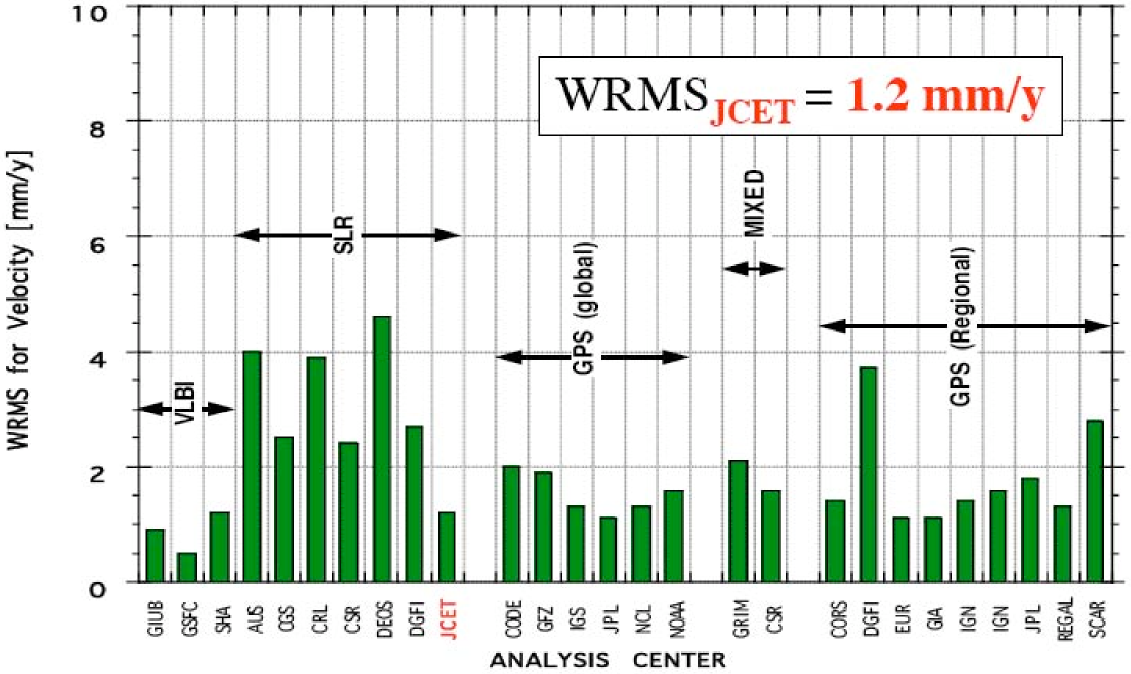


Figure 8. WRMS for velocity components of individual ITRF2000 contributions.

Figures 7 and 8 show for each of the individual contributions to ITRF2000 the level of agreement with the final product, in terms of position and velocity vectors for the common stations. They also display the corresponding quantities for the other individually contributing techniques, as well as in combination. The superior global coverage of the GPS network and the excellent geometric sky-coverage due to multiple simultaneous targets compared to SLR, results in a far more consistent precision across various individual contributions and better agreement with ITRF2000. The marked difference between the majority of the SLR contributions and that of JCET is due to three factors. This contribution is restricted to the period 1993-2000, it allowed for the estimation of geocenter offsets on a weekly basis, and station biases were adjusted where needed due to irregularities in station performance. It is thus obvious, that with a careful approach in the analysis of the existing SLR data, the contribution to a TRF realization can be even in the relative sense, as comparable or even more significant, as any GPS contribution: Position $\mathrm{WRMS}_{\mathrm{JCET}}$ = 2.4 mm vs. six GPS contribution average $\mathrm{WRMS}_{\mathrm{GPS6}}$ = 2.8 mm and Velocity $\mathrm{WRMS}_{\mathrm{JCET}}$ = 1.2 mm/y vs. $\mathrm{WRMS}_{\mathrm{GPS6}}$ = 1.6 mm/y. This is in addition to the unique and undisputable contribution of SLR in the definition of the origin, and the equally shared definition of the TRF scale along with VLBI.

One of the unique advantages of SLR as a technique is its long history and presence, as it has a more or less global network in operation since the early '70s. This allows us to produce a uniform continuous Earth Orientation Parameter (EOP) series with a five-day resolution in the early years and a daily resolution after 1983 or so. The pole trajectory from SLR is shown in Figure 9, while in Figure 10, we plot the variations in the Length of Day (LOD), "draped" on a the integrated LOD which with the aid of benchmark values of UT1 from VLBI, provides the reference surface on which LOD is plotted.

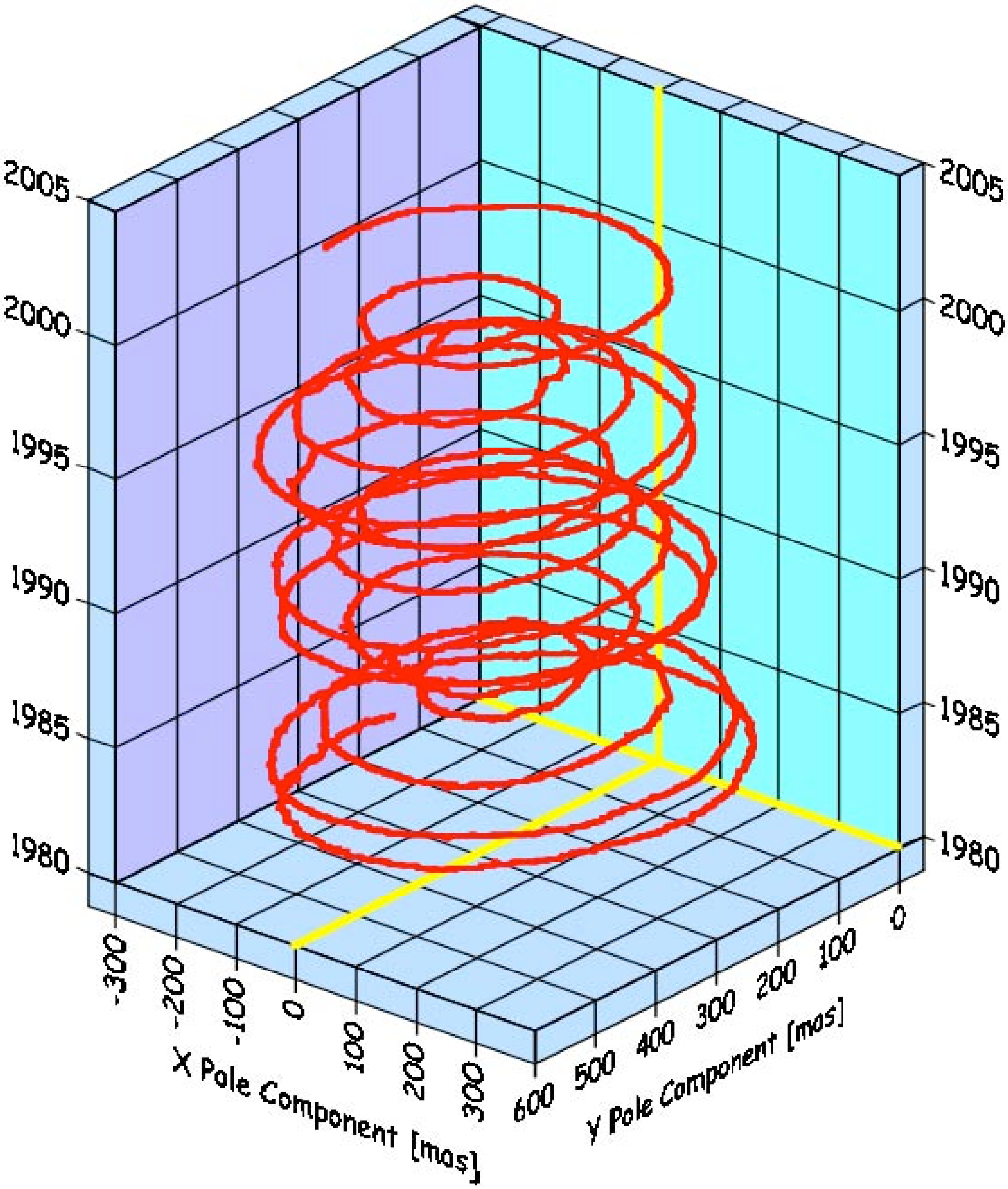


Figure 9. The trajectory of Earth's instantaneous rotational axis 1983-2002.

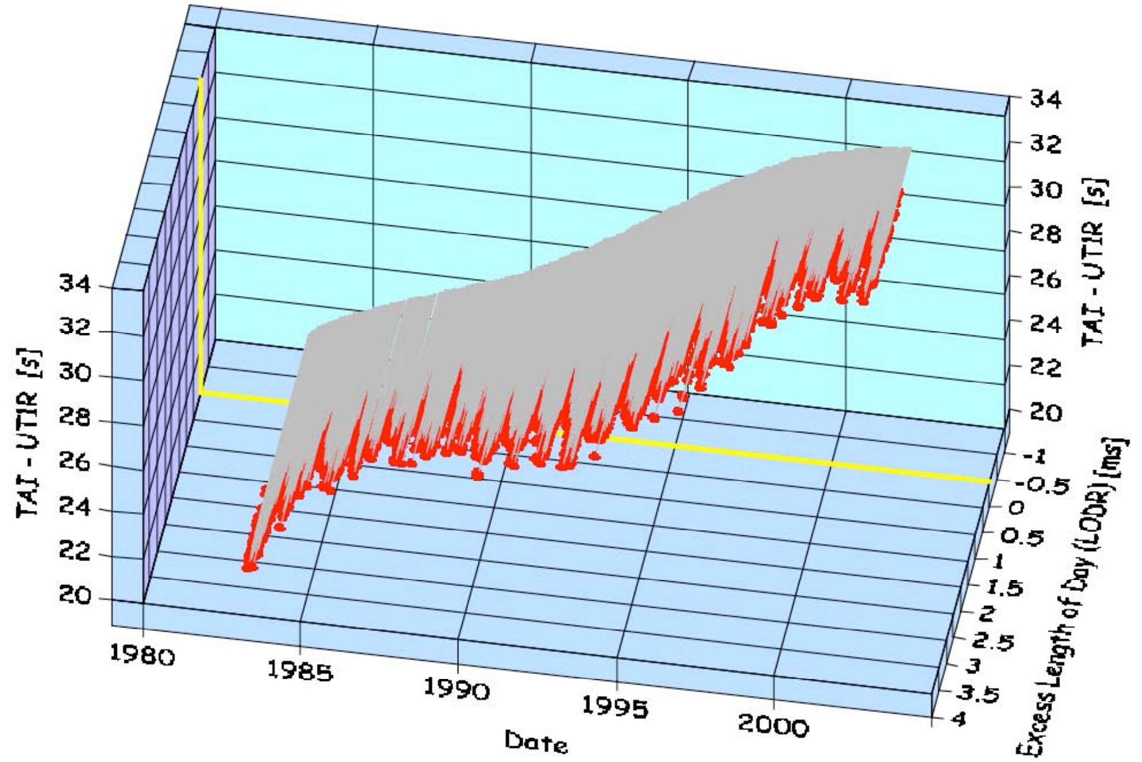


Figure 10. Excess Length of Day (LOD) and integrated UT1 difference with respect to TAI (using VLBI absolute UT1 values as control).

The value of these long in time and high in quality EOP series is in that they provide a check on the orientation of the TRF through the decades. By developing a very accurate TRF at present from (primarily) recent tracking data, we can (using these series) extend its use in analyzing older space geodetic data, collected at a time that the TRF was not available with such great accuracy and we can re-estimate the coordinates of older tracking stations that have since sized to exist, or derive other geophysical parameters of interest (e.g. long-wavelength gravitational coefficients and their temporal variations).

Geophysical Signals from SLR

SLR's direct contribution in the development of the TRF was already mentioned in the introduction and detailed in the previous sections. Here we will give some examples of how through the observation of temporal changes in the long-wavelength gravitational harmonics, it also provides an independent means of detecting geophysical signals and thus contributes in the Global Earth Observation System and in Global Climate Change studies.

We have already seen how the dynamics of the precise LAGEOS orbits are capable of delivering weekly observations of the variation in the location of the geocenter with respect to the center of figure realized by the tracking stations network (Fig. 2). One immediate observation from Figure 2 reveals that although the dominant signals are the annual and possibly a semi-annual harmonic along with high frequency "noise", there are at times significant departures persistent over time from this seemingly periodic behavior. This is very prominent in two cases, during the 1996-1997 and the 2002-2003 periods.

Both of these anomalies happen to be during periods of strong El Niño events [McPhaden, 2004]. Since the phenomenon is primarily equatorial in nature, we investigated the trajectory of the center of mass on the equatorial plane (Figure 11). We notice that while the chaotic motion is confined within a 3 mm radius circle around the mean position, there are periods with systematic excursions from this area of confinement. Generating the trajectory over annual periods we were able to correlate these excursions with the periods of the two El Niño events. They also happen in general longitudinal directions that coincide with the transport of water masses during these events (Indonesia and Polynesia). The magnitude and direction of the shift is consistent with the expected water mass change based on the oceanographic observations of the total sea-surface height changes (Figure 12 for the 2002-2003 case), and the assumption that the real mass change corresponds to about 10-15% of the total observed sea-surface height variation, the remainder majority change being the effect of thermal expansion.

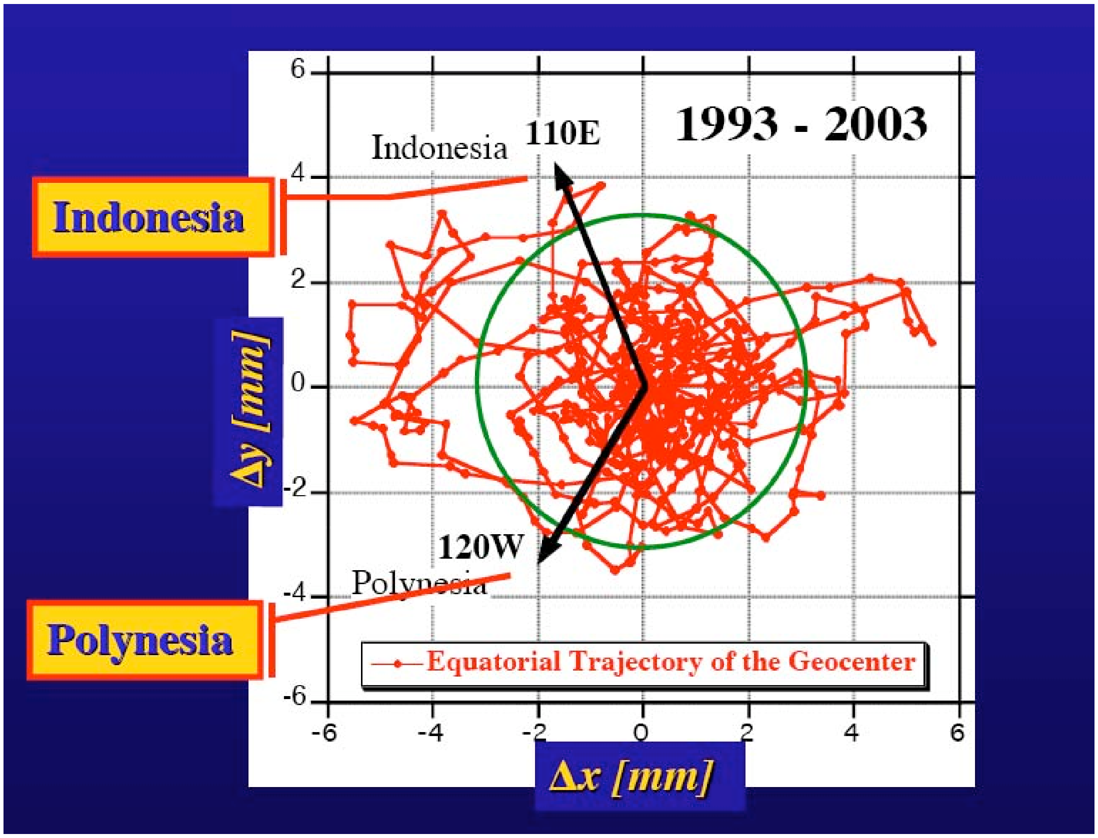


Figure 11. Trajectory of the center of mass projected on the equatorial plane, for the period 1993-2003. The 3 mm radius circle marks an area within which the motion is confined for most of the time. The two excursions between longitude 110E and 120W (and the anti-diametric ones) are correlated in time with the two El Niño events of 1996-97 and 2002-03.

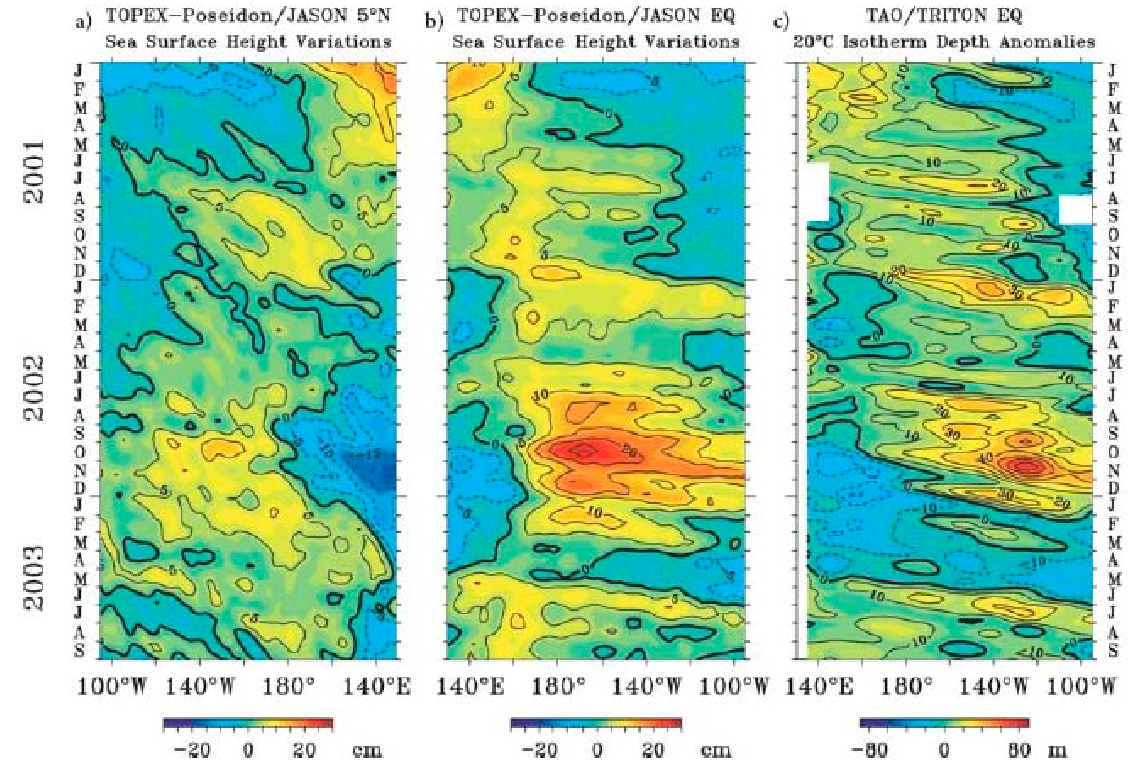


Figure 12. Ten-day anomalies of sea level from a 1° lat/long analysis of TOPEX/Poseidon and Jason altimeter data along (a) 5°N and (b) averaged between 2°N–2°S. Panel (c) shows 5-day 20°C isotherm depth anomalies averaged between 2°N–2°S. Anomalies are relative to climatologies based on data from 1993– 2001, (see original reference for a detailed discussion: Fig. 4, page 683, from [McPhaden, 2004]).

Modeling improvements in the analysis of SLR data

Despite the wealth of interesting and valuable phenomena that SLR currently observes, recent advances in our understanding of the Earth System and the interactions between its components, mandate that we constantly update and improve our modeling and analysis of SLR data, even when the accuracy of the raw data themselves does not change. The expected changes in the level at which we can "fit" the observations with the improved models are nowhere near those that we witnessed a decade ago, but today, with the stringent scientific requirements to resolve geophysical signals at the millimetre and 0.1 mm/y level, changes in our products at that level are very significant and contribute directly in achieving the ultimate goal. Furthermore, since this goal is not a SLR-only affair, we must harmonize our standards, analysis principles and line of products to those commonly accepted by all the other Space Geodetic Services, and sanctioned by the ultimate customer they all serve: the International Earth Rotation and Reference Systems Service (IERS). IERS has recently adopted a new set of Conventions and Standards in 2003, [McCarthy and Petit, 2004]. This new set of models, standards and analysis principles is now being implemented in the main software packages that are used in the analysis of SLR observations. In addition to the new standards, there have also been independently taken initiatives by each technique to improve technique-specific models, whose quality is still far from satisfactory. One such model in the case of SLR is the one that describes the atmospheric delay due to signal propagation through the atmosphere. For decades SLR has relied on a model that was developed in the early '70s, [Marini and Murray, 1973], tuned primarily to the most common laser wavelength used by the systems of the time. Today there is new knowledge about the atmosphere, and new laser systems that operate in a wide range of wavelengths from 355 to 1064 nm and beyond. There is also increased need to separate measurement biases from errors in the atmospheric delay and possible vertical motion at the tracking sites, all of which dictated that we revisit this model and develop a new one that would be applicable today. Here, we will give some examples of the application of these innovations in the SLR data modelling and analysis, for cases that we have already obtained initial results.

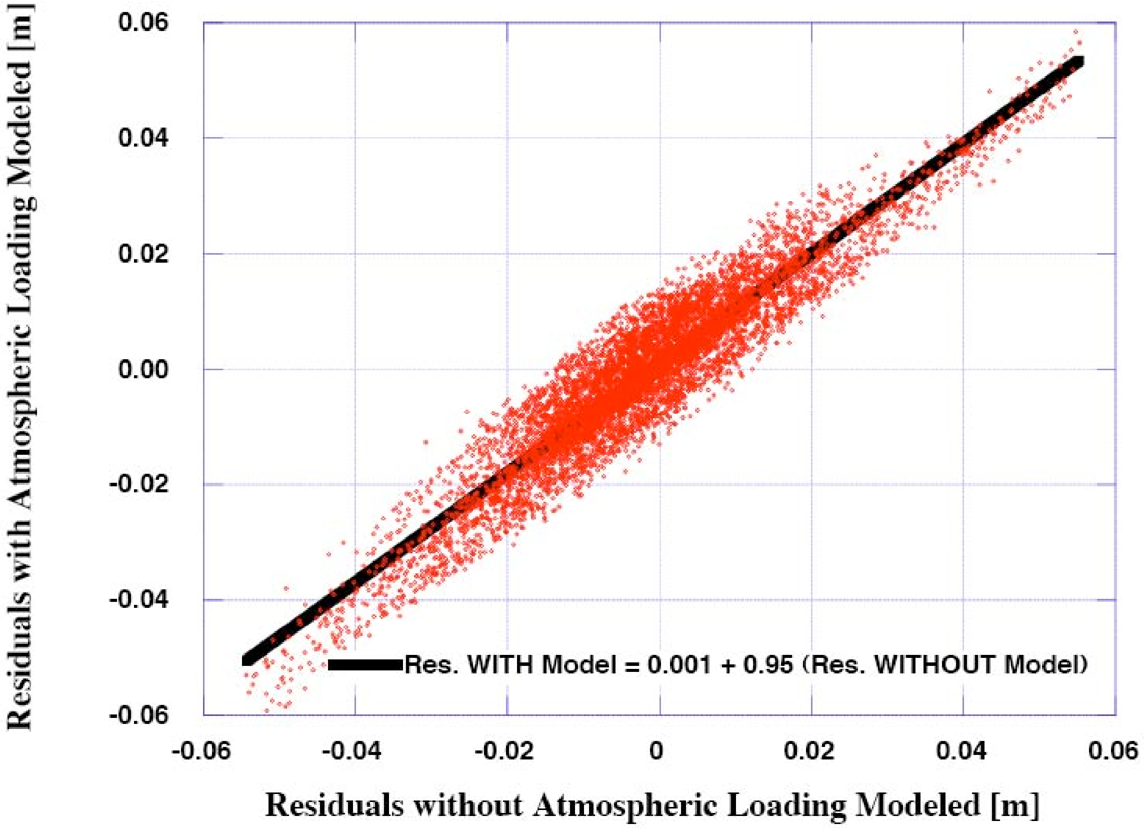


Figure 13. Regression plot of SLR range residuals analyzed in two different modes: the standard mode (x-axis), and the case when atmospheric loading at the tracking sites is modeled. The loading is obtained from NCEP 6-hour global fields [Petrov and Boy, 2004].

One of the topics that has seen a lot of attention and progress lately is the interaction of the components of the Earth System and in particular, their temporal spectrum. Missions such as CHAMP and GRACE were launched to address some specific questions associated with these topics and as a result, we already have a good insight in some areas. As a result of atmospheric circulation and consequent pressure changes at the tracking stations, the crust is regionally loaded with variable loads which in turn cause changes in what we call "station height" over a wide temporal spectrum. This was already recognized for some time, but it is only recently that access to global data sets of these loading effects became widely and routinely available to the analysts at *http://gemini.gsfc.nasa.gov/aplo*, [Petrov and Boy, 2004]. Although inclusion of atmospheric loading will likely have a bigger impact in the analysis of SLR data at the longer wavelengths by removal of such strong signals as the annual and seasonal, the benefits can be seen already when we examine a 28-day LAGEOS arc that is analyzed with the inclusion of these temporal changes. Figure 13 shows the regression of the range observation residuals to two, otherwise identical models, one of which includes the atmospheric loading signal, and one that does not. Apart from an insignificant (0.1 mm) bias, the residuals with the loading modeled are 5% smaller than those that do not. When a long record of SLR data is analyzed with atmospheric loading included, what we expect to see is a much less noisy behavior in the recovered station heights, with a substantially systematic-free variation, and similar improvements in the recovered scale-related parameters of the TRF (i.e. $GM_{\oplus}$). Another model component that is also associated with "geophysical fluids" circulation is the effect (attraction) of their variable mass on the satellite itself.

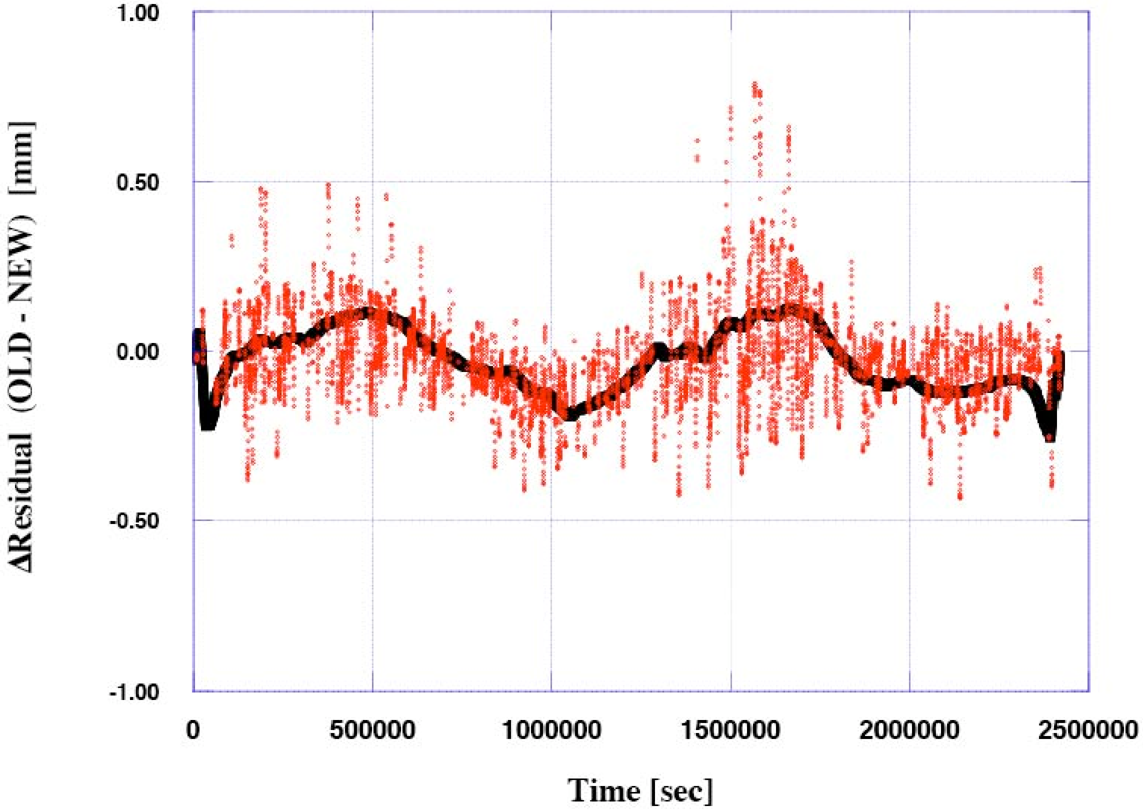


Figure 14. Differences of SLR range residuals analyzed in two different modes: using the IERS Conventions 1992(?) model for tidal motions at the tracking sites, and the case where the IERS Conventions 2003 model is used.

This is not included in the analysis shown in the above figure, GRACE however is already observing this at monthly intervals and can provide the appropriate information. Furthermore, the same process that produces the loading signal of the atmosphere produces in parallel the required changes of the gravitational harmonics at the same 6-hourly intervals. It is thus possible now to include this effect in our future analyses, and because these variations are available for all years for which SLR data exist, we can even retroactively improve our analyses adding further value to the older data. The magnitude of the effect is rapidly diminishing with altitude of course, so this improvement is far more important for the low altitude missions than for satellites like LAGEOS.

The adoption of the new IERS Conventions and Standards improves the modeling of the tidal variations in the station coordinates, with the height being the primary beneficiary again, as in the case of atmospheric loading. Figure 14 shows an example for a 28-day arc fit with LAGEOS data, of the effect this change has on range observation residuals when we move from the old model to the new. Again, we stress that the change in itself is not dramatic, ±0.5 mm, but if we compare it to signals of global change that we are after today (0.1 mm/y), it is very significant, and it can easily introduce systematic variations which can be misinterpreted.

Improving the geophysical modelling is not the only area where significant advances were achieved over the past, in some cases based in part or entirely on SLR observations. We have also progressed in our ability to understand and better model the behavior of the targets themselves, and thus improve the quality of the orbits we derive on the basis of our observations. Considering that these orbits act as the quasi-inertial frame with respect to which we monitor the terrestrial frame and its evolution, along with a myriad of geophysical signals, it is an easy conclusion that these improved orbits, can only result in further improvements in the development and monitoring of the TRF.

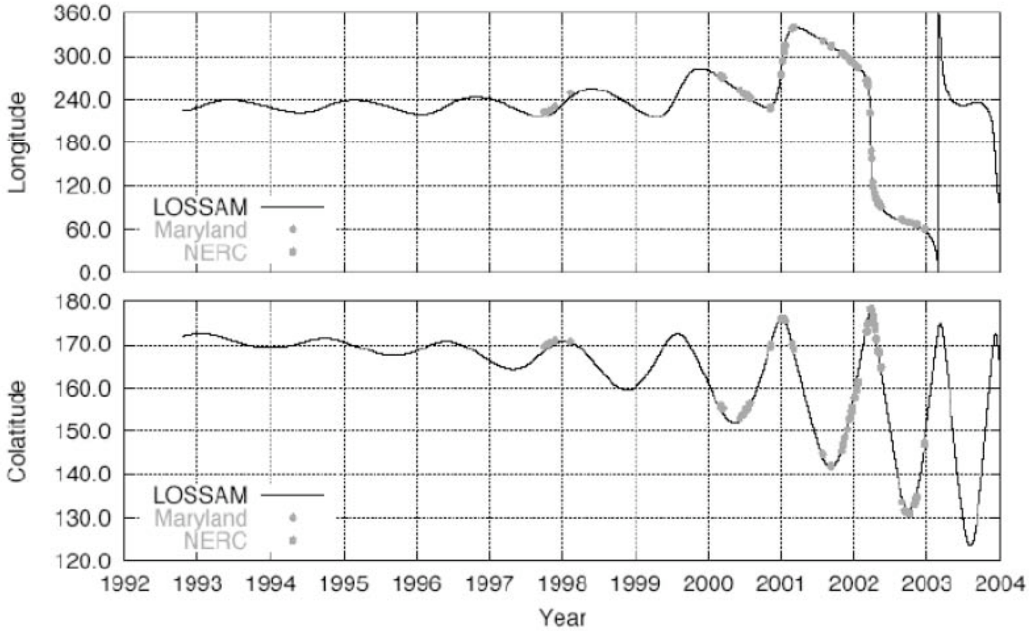


Figure 15. Spin-axis evolution for LAGEOS and LAGEOS 2 [Andrés et al., 2004].

With the LAGEOS satellites being the primary targets in this effort, the majority of investigators also focus on improving these particular targets' orbital models. A recent significant improvement in this area is the development of a better model for the evolution of the spin-axis orientation for the two LAGEOS [Andrés et al., 2004]. This improvement was partially enabled by improved SLR observations and analysis, and in part from the existence of optical observations from various locations on Earth. These improved models are now used in the analysis of LAGEOS SLR observations and their inclusion resulted in the reduction of the magnitude of *ad hoc* accelerations, previously used in our models to account for phenomena that are not entirely understood yet [Lucchesi et al., 2004].

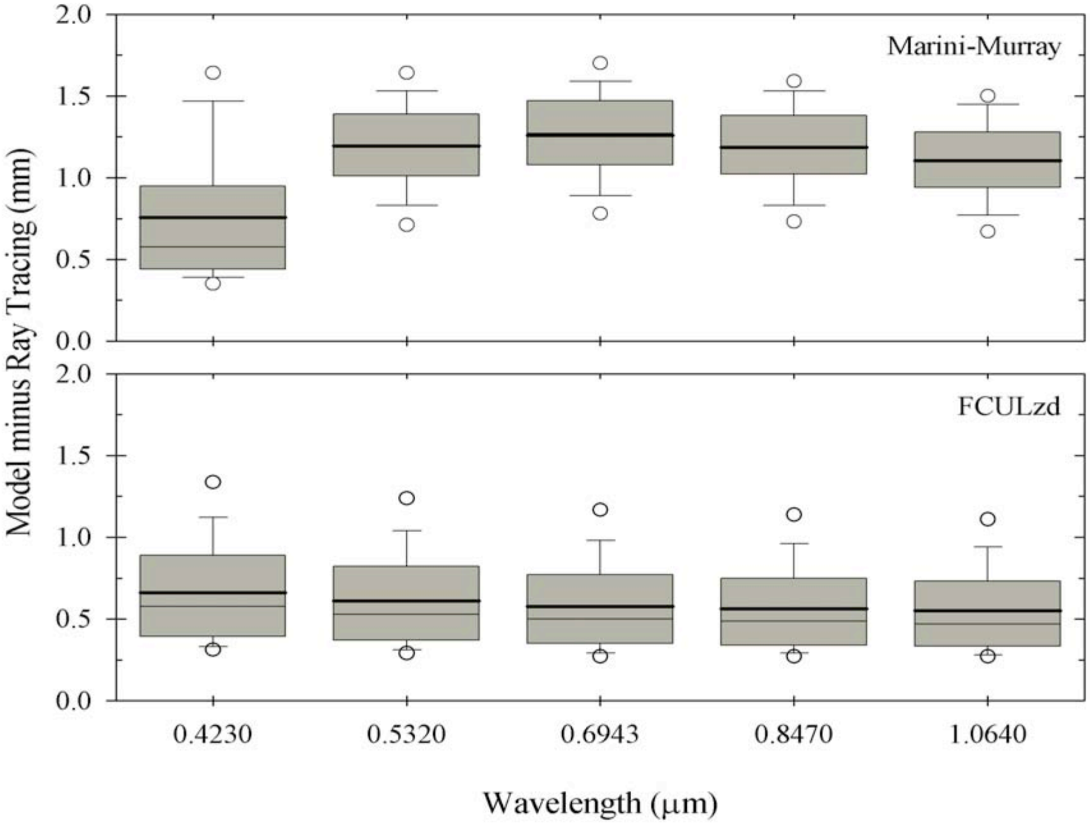


Figure 16. Validation statistics for the Mendes-Pavlis (MP) and the Marini-Murray (MM) models in the 423-1064 nm band. Box-and-whisker plots using the RMS values obtained at each individual radiosonde station used in the validation. The statistical quantities represented are the median and the mean (thinner and thicker lines inside the boxes, respectively), the 25th and 75th percentiles (vertical box limits), the 10th and 90th percentiles (whiskers), and the 5th and 95th percentiles (open circles), from [Mendes and Pavlis, 2004].

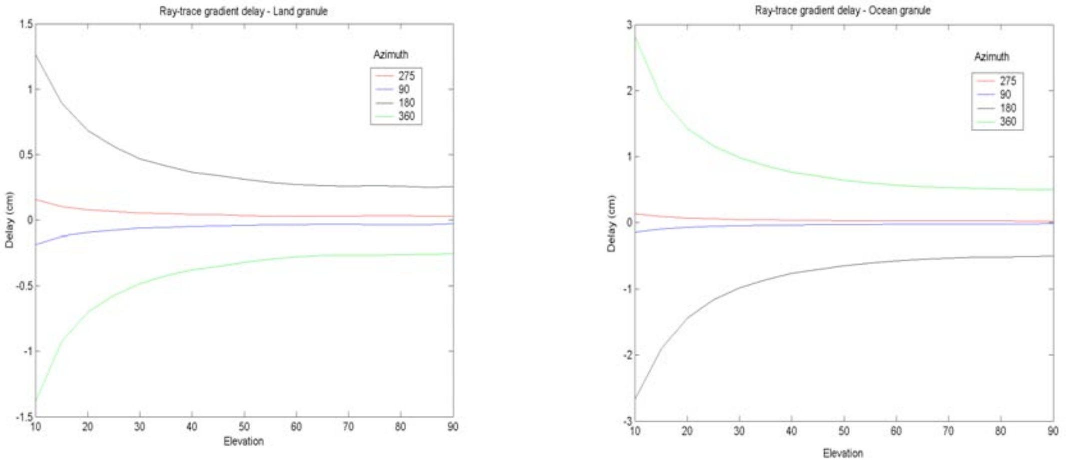
One common problem for all space techniques is the propagation of the transmitted and received signals through space, and primarily, through the atmosphere and ionosphere.

Laser (optical) signals are impervious to ionospheric effects, they are however sensitive to atmospheric signal retardation. The hydrostatic zenith delay due to the atmosphere is of the order of 2.5 m, while the non-hydrostatic part, due to the water vapor in the troposphere, is about 10% of the hydrostatic. The effects of both delays are amplified greatly as we move away from zenith towards low elevations. The quality of the modeled effect is dominated here by the so-called "mapping function" (MF), which maps the predicted zenith delay (ZD) to the true elevation that the observation is taken.

Traditionally SLR observations were taken above the 20° degree elevation for safety reasons. With the installation of radars at most tracking sites, it is now possible to range at very low elevations, as low as the surrounding orography and nearby obstructions permit. Collecting observations at low elevations allows for a better separation of measurement biases and station height local variations. This is therefore a very important reason to pursue the low elevation data. The traditional atmospheric refraction model used since the early days of SLR is that of Marini and Murray (MM), published in 1973, as we already mentioned earlier. The model provides high quality atmospheric delay estimates above 10° elevation, in a fashion that the ZD and the mapped ZD are all computed in a single step. The model was also tuned to a single wavelength, with quickly degrading performance as one moved away from that wavelength. While atmospheric modeling for radiometric techniques as GPS, VLBI and DORIS, where the effects are much larger and variable, was making quick progress with a multitude of improved MF and ZD models, SLR kept using the very successful MM model since its performance was deemed adequate. In recent years however, we not only found a need for low elevation observations, a number of new systems initiated operations at two-colors, in hopes to use them for a direct estimation of the atmospheric delay [Degnan, 1993]. Suddenly, we were presented with the task to analyze data at wavelengths that ranged from 355 nm all the way 1064 nm. Furthermore, the performance of the MFs had to be improved and the atmospheric corrections had to be computed on the basis of standards recommended and adopted by the International Association of Geodesy (IAG) [Int. Union of Geodesy and Geophysics (IUGG), 1999], not in existence during the development of the MM model.

This presented a new challenge, and following the adoption of the IAG resolution, ILRS established a Refraction Study Group to address these issues. Several of its members in collaboration over years, initially developed a new and improved MF valid down to 3° elevations [Mendes et al., 2002], and later, a new, unbiased ZD model, applicable with the same performance over the entire spectrum of SLR wavelengths of interest [Mendes and Pavlis, 2004]. Figure 16 summarizes the statistics of the validation of the new ZD model across the 423-1064 nm band. Results for 355 nm were excluded from the graph for clarity, since MM under-predicts the delay at this wavelength by a whopping 7 mm.

With the MF and the ZD models improved, one final area in media propagation modeling that had not received any attention since the early days of NASA's Crustal Dynamics Project was that of the effect of horizontal gradients in the atmosphere. Again, the radiometric techniques, because of the order of magnitude increased sensitivity in these effects, had made strides in this area over the past decades, and they are now routinely including this modeling in their analyses [MacMillan and Ma, 1997].



(a) **(b)**

Figure 17. Predicted atmospheric delay (cm) due to horizontal gradients: (a) over a land area and (b) over an ocean area. Based on the AIRS ray-tracing method at four cardinal azimuths and at all elevations, on a specific date.

It was therefore time for the SLR community to address this source of error, determine how serious it is, and following that, develop the appropriate modeling. This effort is now underway with the aid of near-real-time globally available remote sensing data for the atmosphere from space missions, primarily from the AIRS system on NASA's AQUA platform (for more details see [Hulley et al., this proceedings]). The initial results from [*ibid.*] indicate that horizontal gradients are not nearly a problem for SLR as they are for radiometric techniques (Figure 17), a result that was already theoretically expected. On the other hand, the effect of the gradients can be limiting accuracy of the SLR products in the case of the most stringent requirements, and in cases where SLR sites are located at the coast with large bodies of water on one side, it may even introduce systematic, seasonal errors. The comforting result from this study is that existing models can be extended and applied to SLR wavelengths with great success, so that even in the absence of regional observations of the atmosphere in the surroundings of a tracking site, we can apply the effect of horizontal gradients on the basis of analytical models and with input from the meteorological data collected at the site, at least adequately enough for most applications. The investigation though continues and we look forward to first results by about a year from now.

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 a unique and irreplaceable 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 discussed with examples, the improvements in the analysis and modeling of SLR observations as we embark in the development of a new realization of the TRF (ITRF2004). 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.

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