Improved Modeling Approaches Towards the mm SLR

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Abstract

Accuracy requirements for the International Terrestrial Reference Frame (ITRF) are becoming increasingly more stringent, especially with regards to its origin definition and its scale stability. Satellite Laser Ranging (SLR) contributes unique information on the origin, and along with VLBI, for its absolute scale. Advances in our understanding of the coupling between the sub-components of system Earth require that we revisit our current modeling used in the reduction of SLR data. Over the past few years, the inclusion (or not) in our models of high frequency effects of the temporal gravity signals due to mass redistribution in the terrestrial system, has been a topic of heated discussions at venues such the EGU, AGU and various workshops. With the recent release of numerous products from global circulation models and, satellite and terrestrial observations, we are now able to examine the effect of such improved modeling in the analysis of several years of SLR data. We present results from such analyses and compare them to our nominal results, based on the currently accepted ILRS standards. Depending on the outcome of these tests, we anticipate that in the near future, ILRS will formulate a proposal to IERS for modification of the analysis standards related to the products contributing to the establishment of the future ITRFxx.

Introduction

The International Terrestrial Reference Frame (ITRF) accuracy requirements are becoming increasingly more stringent, driven primarily by those dictated by the Global Geodetic Observing System—GGOS. It is now commonly accepted that the future ITRF should exhibit 1 mm accuracy in the origin of the reference frame at epoch and 0.1 mm/y stability over time [Pavlis et al., 2008]. One of the primary techniques contributing to the development of the ITRF is Satellite Laser Ranging (SLR). SLR determines uniquely the origin of the ITRF and along with VLBI, its scale. For many years now SLR has also observed mass redistribution in the Earth system [Pavlis, 2002], providing unique estimates prior to the launch of GRACE [Tapley et al., 2004]. With the increased maturity in the GRACE products and the proliferation of global fields of atmospheric, oceanic, and hydrological processes, it is now high time to consider the forward modeling of these processes in the analysis of SLR data for the establishment of the TRF. These observations form the motivation behind the work that is reported here, focusing on the possible improvements in the currently adopted standards for SLR data analysis. We will present results form limited tests with various ancillary data sets, demonstrating the level of expected improvement in the results, once these are considered in the a priori model. Although these are presently focused on the analysis of LAGEOS data only, it is planned that in subsequent stages we will extend the most promising model improvements to LEO targets in an effort to make their contribution useful and of acceptable accuracy for inclusion in the development process of the ITRF.

Candidate models under consideration

One of the first improvements to be considered is of course the time varying gravitational signals that GRACE observes at monthly intervals. With several years of GRACE data accumulated by now, it is even possible to derive sufficiently high-resolution models that can be used even during the time period prior to GRACE's launch. In this fashion we can benefit and improve the results from reanalysis of historical SLR data collected long before the GRACE era. In addition or instead if these, we can also consider the inclusion of other models, namely:

- Extended temporal gravity variations
  - NCEP or ECMWF (3 or 6 hr temporal resolution, 0°.25, …)
  - GRACE-derived monthly fields & de-aliasing products
  - Other combinations
- Atmospheric loading (from NCEP or ECMWF)
- Hydrological loading (e.g. GLDAS)
- New ocean tides (e.g. GOT04.7 or more recent) with proper treatment for the atmospheric tides
- Atmospheric refraction from 3-D atmospheric ray tracing (ART) to include atmospheric gradients
- Albedo from global satellite-based fields (higher degree-order seasonal model)

CSR RL04	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
2002												
2003												
2004												
2005												
2006												
2007												
2008												

Figure 1. The monthly GRACE fields that were used (green) in this study to derive the analytical model of time varying gravity for very long wavelength (temporal) signals.

The work reported here addressed through limited tests for a few years of LAGEOS and LAGEOS 2 SLR data analysis, the contribution of the GRACE fields, the atmospheric fields from ECMWF, the improved tidal models, and the use of 3-D ART corrections [Hulley and Pavlis, 2007] for the atmospheric refraction instead of analytical models and surface data [Mendes and Pavlis, 2004].

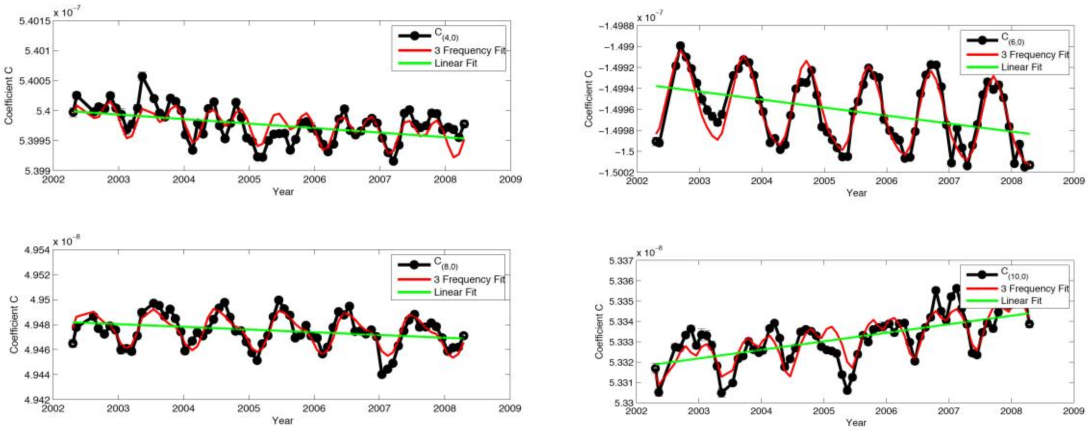

Figure 2. Temporal variations in the even zonal harmonics for degree 4 to 10 observed by GRACE and the linear (green) and harmonic (red) analytical model fitted to them.

GRACE-derived time varying gravitational model

We used the six-year monthly series from CSR's release 4 (RL04) available from April 2002 up to present (Fig. 1), along with the associated de-aliasing product and estimated a set of mean coefficients at epoch 2000.0, along with a secular linear trend and annual, semi-annual and seasonal terms for the entire field to degree and order sixty. Examples of the derived models are shown in Figure 2 for select harmonic coefficients. These coefficients and their variations were then used as the basis for the Precise Orbit Determination (POD) step of the SLR data. The results were then compared to those based on the standard model used for the development of the official ILRS weekly products. In terms of gravitational model, the standard model uses CSR's GGM02C and the tidal model from Goddard, GOT00.2. The current tests used the slightly improved tidal model GOT04.7 that differs from GOT00.2 primarily near the coastlines, which however has implications for the computation of the loading effects, especially for coastal sites.

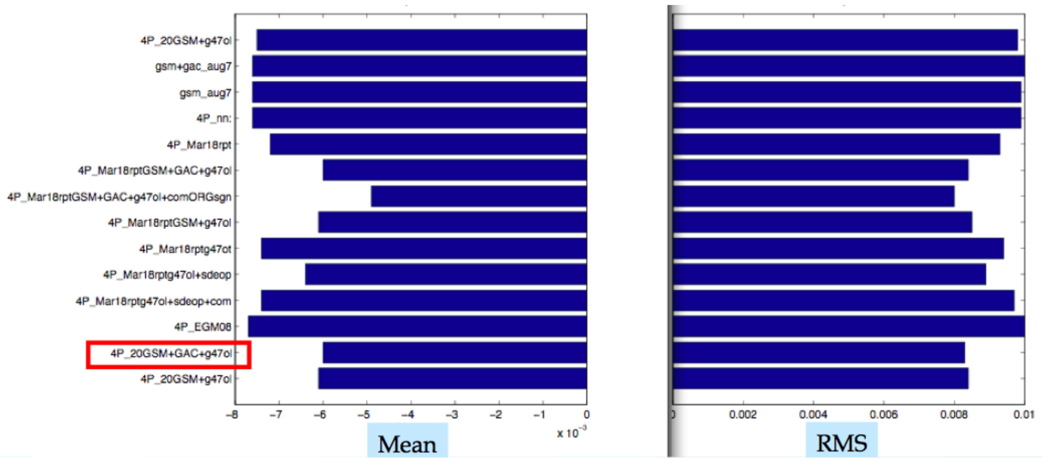

Figure 3. Residual mean and RMS statistics [m] of fits to LAGEOS SLR data collected at Herstmonceux, UK, using a variety of background models for gravity, tides, etc..

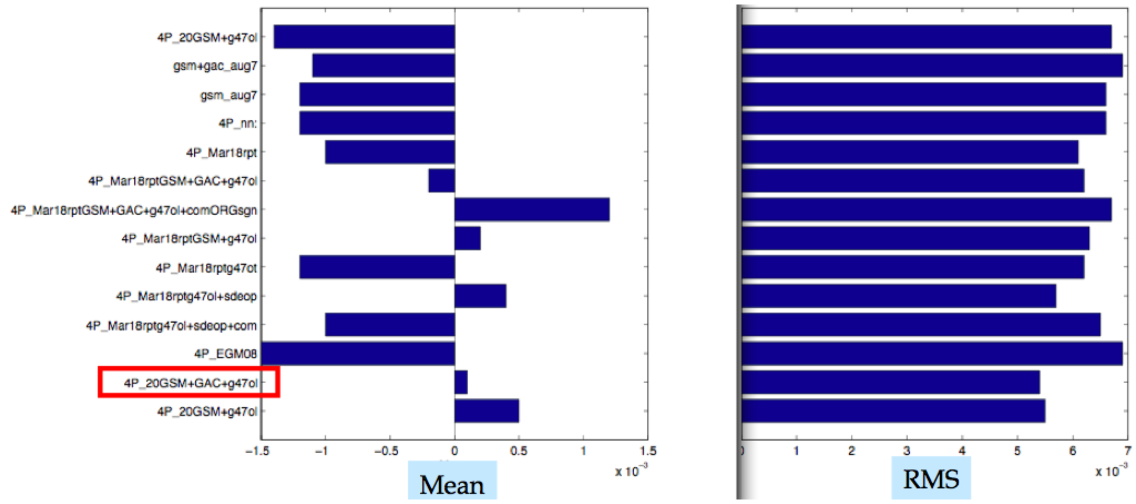

Figure 4. Residual mean and RMS statistics [m] of fits to LAGEOS SLR data collected at Yarragadee, Australia, using a variety of background models for gravity, tides, etc..

Various combinations of improved models were used in reducing the SLR data, each time comparing the mean and RMS residual for each station with respect to those obtained from the standard model as well as the previous tests. We tested each station separately rather than the result for the ensemble of the participating stations in each arc, since not all stations are of equal quality and the ensemble statistics depend largely on the adopted relative weights, something that is a rather subjective process. Our conclusions were drawn primarily from the results of the strong and consistent stations in the network. An example is given in Figure 3 for the Herstmonceux site in UK and for Yarragadee, Australia, in Figure 4.

An examination of the best stations in the network revealed that the preferred model by the data is the one described by the model we fit to the GRACE monthly fields, augmented by the GRACE-supplied de-aliasing and the new Goddard tidal model GOT04.7. Even though there were slight variations between the various sites, the majority vote was for the aforementioned model.

Atmospheric loading modeling

The effect of atmospheric circulation (mass redistribution) was partially modeled through the adopted GRACE-derived gravitational model of the previous section. This is because the modeled effect applies only to the orbit, ignoring entirely the loading effect that modifies primarily the tracking sites' height over the entire spectrum. Using the meteorological global fields of ECMWF we can derive a correction to each station's position due to this loading effect. This has been pioneered as a service since a few years now [Petrov and Boy, 2004], and results are available for various operational and experimental fields from ECMWF (versions v0, v1 and v2), as well as from NCEP:

"v0": 1970/01 - 2002/08: ECMWF Reanalysis (ERA40), with a spatial resolution of 1.125 degrees
"v1": 2000/12 - 2006/12: ECMWF Operational, with a spatial resolution of about 0.350 degrees
"v2": 2005/10 –present: ECMWF Operational, with a spatial resolution of about 0.250 degrees

Because of the existence of these multiple fields, we chose to analyze SLR data in 2001 and 2006, so that we can test the maximum possible set of these fields. The results obtained from these tests were compared to those obtained without atmospheric modeling, and the statistics of their differences are summarized in Table 1.

Table 1. Statistics of RMS differences for the 2001 & 2006 LAGEOS SLR data reductions with atmospheric loading modeling from various ECMWF releases.

Test Case	Points (weeks)	Mean	Median	RMS	Std Deviation
ΔRMS v0-NO*	52	3.4	2.7	4.45	2.87
ΔRMS v1-NO	104	2.9	2.1	4.31	3.16
ΔRMS v2-NO	52	2.7	1.7	4.09	3.08
ΔRMS v1-v0	*52*	*0.4*	*0.0*	*0.92*	*0.82*
ΔRMS v2-v1	*52*	*1.7*	*1.4*	*2.58*	*1.96*

*NO indicates no atmospheric loading modeling

The top three rows of Table 1 show that any of the three versions of ECMWF fields, when used to derive loading at the tracking sites improves the results with an average reduction in the overall RMS of fit of the order of 3 mm in the mean (or 2 mm median difference), and a similar magnitude of variation about the mean over the tested weeks.

The last two rows compare the three variations of the ECMWF released fields, as "seen" through the orbit filter controlled by SLR tracking data. Evidently, the difference between v0 and v1 is insignificant given the magnitude of the mean and the corresponding RMS. Apparently, going from 1°.125 resolution down to 0°.350 is not making a huge difference. On the other hand, the difference between v1 and v2 is much larger, although that one does not seem statistically significant either when one considers the scatter associated with it. Additionally, the comparison of v1 and v2 is over 2006, when the data that are used to form the ECMWF fields are quite different from those used in 2001 (when we compared the v1 to v0), dominated by global fields obtained from satellite missions. Irrespective of which ECMWF product one uses, it is evident that there is a significant change (improvement) in the fits to SLR data and if one compares this change to the present day state-of-the-art results, the conclusion is that we can no longer afford to not model such effects if our goal is to achieve millimeter or better geodesy.

Advanced refraction modeling

SLR is an optical technique and as such it is not affected greatly by atmospheric refraction as other space geodetic techniques operating in the microwave region of the spectrum. Nevertheless, when we strive for mm-level accuracy, even the otherwise small effects of horizontal gradients in the lower atmosphere must be accounted for. One proven way to do this is to compute refraction corrections along the laser beam path directly from three-dimensional ray tracing through the meteorological fields that are now routinely available. This method was pioneered and tested with the analysis of two years of SLR data by Hulley and Pavlis [2007]. The concept is described in the graphic and equations shown in Figure 5. As discussed in [ibid], the SLR data for 2004-2005 were corrected using refraction corrections obtained using the 3D ART approach, based on three different global fields: ECWMF, NCEP and the satellite observations from the AIRS instrument on board the AQUA NASA platform.

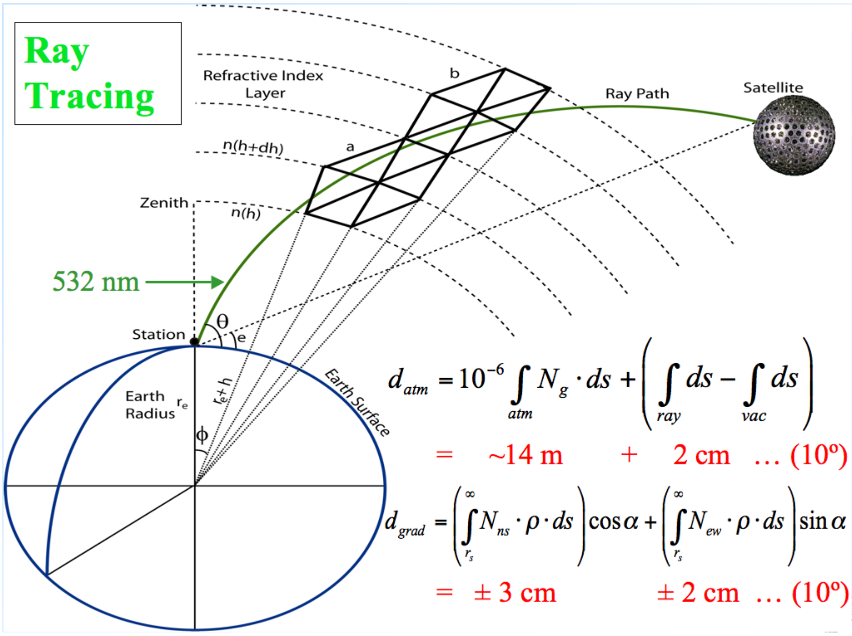

Figure 5. The three-dimensional ray tracing approach to computing the total atmospheric delay along the path of a SLR range observation.

The comparison of atmospheric gradient variations obtained from the three sources agreed in generally very well, however, it is quite apparent when one looks at the results shown in Figure 6 for the Herstmonceux site, that AIRS and ECMWF are in much better agreement than any other pair.

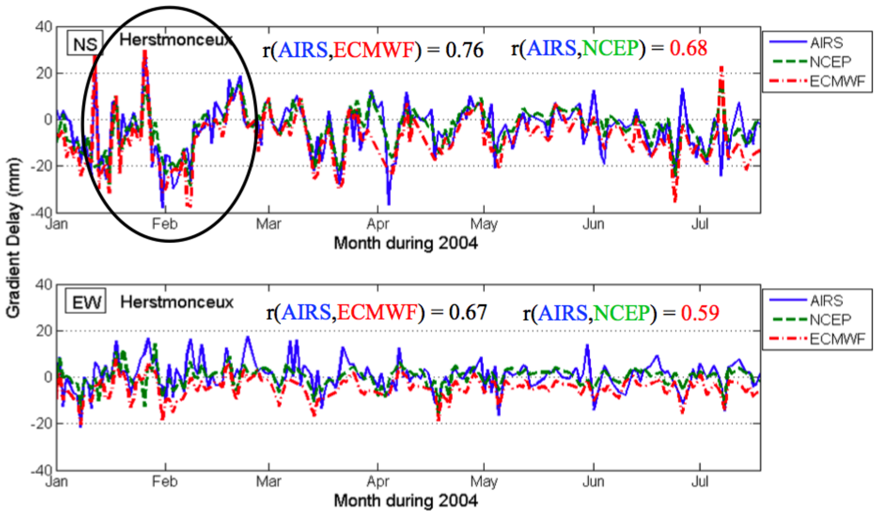

Figure 6. Atmospheric gradients at Herstmonceux during 2004, from three different source fields (AIRS, NCEP and ECMWF).

After applying these corrections to the SLR data, the RMS residual fits improve considerably, indicating the importance of these corrections for future analyses. Statistics of these comparisons are shown in Table 2. From these results it is evident that 3D ART with AIRS-observed meteorological fields is the best approach, explaining almost 25% of the residual variance. An alternate approach where the isotropic delay is modelled through the analytical model of [Mendes and Pavlis, 2004] and the gradients are obtained from 3D ART is not as effective, explaining only 14% of the variance for the same data.

Table 2. Residual statistics of SLR data corrected with 3D ART atmospheric delays.

Method	**ΔBias (mm)**	**$\Delta\sigma^2$ (%)**
AIRS		
RT_{grad}	0.3 ± 0.3	14.0
RT_{3D}	0.9 ± 1.1	**24.8**
ECMWF		
RT_{grad}	0.1 ± 0.5	10.8
RT_{3D}	0.6 ± 1.2	**22.5**

Conclusions and future plans

The stringent accuracy requirements of GGOS require amongst other the improvement of the a priori models necessary for the reduction of the space geodetic data. One of the most significant errors in techniques sensitive to gravitational variations are the temporal signals caused by the continuous mass redistribution in the Earth system. We have shown that using the available GRACE monthly fields we can generate models for these variations that can be used in orbital modeling along with consistent improved tidal models, to significantly reduce the residual variance. Similarly, the use of meteorological fields to derive the corresponding loading effects at the tracking stations can further explain part of the remaining variance. A final improvement is the computation of the entire atmospheric delay using meteorological fields, especially those obtained from global satellite observations, in order to properly account for the horizontal gradients which are otherwise ignored. Implementing these changes in the future reduction of SLR data will result in significantly improved products with emphasis on consistency over time.

The currently envisioned schedule for the implementation of the new models is to follow the completion of the tests of various models by end of 2008, by which time the ILRS reanalysis for the development of the ITRF2008 should be complete also. Once we have a final version of the ITRF2008 released, we will be ready to begin a re-analysis of the entire LAGEOS 1 & 2 data set from ~1983 to present in 2009, to be ready for a new product that can be used for experimental versions of a new ITRF. With the primary set of satellites completed, we can then apply these models with appropriate resolution to LEO satellites and reduce data over the same period to test their quality for future contributions to the development of the ITRF.

References

Hulley, G. C. and E. C. Pavlis, (2007), A ray-tracing technique for improving Satellite Laser Ranging atmospheric delay corrections, including the effects of horizontal refractivity gradients, *J. Geophys. Res.,* 112, B06417, doi:10.1029/2006JB004834.

Mendes, V. and E. C. Pavlis, (2004), "High-Accuracy Zenith Delay Prediction at Optical Wavelengths", Geophys. Res. Lett., 31, L14602, doi:10.1029/2004GL020308.

Pavlis, E. C., (2002), Dynamical Determination of Origin and Scale in the Earth System from Satellite Laser Ranging, in *Vistas for Geodesy in the New Millennium*, proceedings of the 2001 International Association of Geodesy Scientific Assembly, Budapest, Hungary, September 2-7, 2001, J. Adam and K.-P. Schwarz (eds.), Springer-Verlag, New York, pp. 36-41.

Pavlis, E. C. et al., (2008), "Observing Systems Needed to Address Sea-level Rise and Variability", in *Understanding Sea-level Rise and Variability*, Aarup, T., J. Church, S. Wilson, and P. Woodworth (eds.), Blackwell, Oxford (*in press*).

Petrov, L., and J.-P. Boy, (2004), Study of the atmospheric pressure loading signal in VLBI observations, J. Geophys. Res., 109, B03405, doi:10.1029/ 2003JB002500.

Tapley, B. D., S. Bettadpur, M. Watkins and Ch. Reigber, (2004), "The gravity recovery and climate experiment: Mission overview and early results", Geophys. Res. Lett. 31 (9).