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Satellite Laser Ranging Applications for Gravity Field Determination

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Abstract. *While the GRACE mission is providing an unprecedented insight into the time variations in Earth's gravity field, the determination of the longest wavelength gravity field components from satellite laser ranging (SLR) is still an important component. In particular, GRACE is insensitive to the geocenter variations that are well-observed by SLR. The non-tidal annual geocenter motion reflects the largest-scale (equivalent to degree-1) seasonal mass redistribution in the Earth system, so it is essential for a complete description of the total mass transport. With two decades of SLR tracking from LAGEOS-1 and -2, it is also possible to look for long-term non-linear geocenter motion, which will reflect non-steady mass redistribution such as accelerated glacier and ice sheet mass loss. In addition, the GRACE estimates for the degree-2 zonal coefficient (J2) are affected by apparent tide-like aliases. SLR provides not only an estimate that is essential for the GRACE mission period, it also provides the context for the more recent changes compared to the history of J2 variations over more than three decades. The SLR time series of the low degree terms provides the long-term history of the longest wavelength gravity changes, which should be continued not only through the likely gap after GRACE but also during the GRACE Follow-On mission.*

Introduction

Satellite laser ranging (SLR) has been essential for determining the longest wavelength components of the Earth's gravity field over the last few decades. These components include 1) GM, which strongly influences the scale of SLR reference frame, 2) geocenter, which is equivalent to the degree-1 mass variations that are not well-observed by GRACE, and 3) the degree-2 geopotential harmonics, particularly C20. In addition, SLR, likely in combination with GNNS tracking data from GRACE or other satellites with good accelerometers, will be essential for filling the likely gap between GRACE and the GRACE Follow-on mission. Finally, with the determination of very accurate mean gravity field models by GRACE, particularly for the zonal coefficients above degree 2, SLR data to the LAGEOS satellites have been used to confirm a gravitational effect predicted by the General Relativity.

The scale of the Terrestrial Reference Frame (TRF) and SLR

The scale of the TRF from SLR is determined from the speed of light, orbital dynamics (including relativistic considerations), and the LAGEOS center of mass offset (CoM). From these, we can derive the estimate for GM, which scales the satellite orbit and thus strongly influences the TRF scale. It is essential when estimating GM that the other quantities that can influence the scale are estimated, especially the station heights, since the scale of the background TRF will strongly constrain the estimate of GM if they are not free to adjust. The value currently in use was determined in 1992 from 5 years of LAGEOS-1 data (based on a nominal value for the CoM of 251 mm) (Ries et al., 1992). At the time, the accuracy of the troposphere refraction correction model was uncertain, and a conservative estimate was adopted, leading to an error estimate for GM of ~2 ppb (parts per billion). With the availability of an updated troposphere model (Mendes & Pavlis, 2004) and using both LAGEOS satellites, the results suggested that the troposphere model was not a limiting factor; GM changed by less than 0.5 ppb. The limiting factor was instead found to be the LAGEOS CoM model. Each 3 mm of error in the CoM corresponds to 1 ppb error in GM (and ~0.8 ppb error in the SLR reference frame scale). Assuming that the uncertainty in the CoM model is under 2 mm, a new estimate was obtained for GM = 398600.4416 ± 0.0002 km^3/s^2. This was not significantly different from the current standard, and no change in the conventional value appeared to be warranted. Further analysis will be conducted with the station dependent CoM model adopted by the ILRS. It is interesting to note that the small difference in GM from LAGEOS-1 and 2 is equivalent to 1.2 mm difference in the mean CoM; LAGEOS-1 appears to be about 1 mm larger than LAGEOS-2.

Geocenter variations

The variations in geocenter/degree-1 are not observable by the GRACE K-band ranging system (and only weakly observable from the GRACE GPS tracking), yet they represent the longest wavelength mass variation and are essential to get the complete picture of the seasonal mass redistribution. Currently, there are two sources of regular monthly estimates, available at http://podaac.jpl.nasa.gov/dataset/TELLUS_1_DEG_COEF. Swenson, Chambers and Wahr (2008) combine the GRACE monthly estimates with a numerical ocean model to obtain the degree-1 variations. The amplitudes of the annual variations in X and Y are reasonably consistent with SLR, but the amplitude in Z is about half that seen from SLR (which may affect high latitude studies). The Center for Space Research (CSR) provides monthly geocenter estimates from SLR to 5 satellites (Cheng et al., 2013) as part of the same solution that provides the replacement value for C20 given in GRACE Technical Note 7. The SLR monthly values, illustrated in Figure 1, are rather noisy at the monthly time scale, and possible approaches to smooth the series include applying a wavelet filter or interpolating 60-day estimates that do not exhibit the same level of scatter.

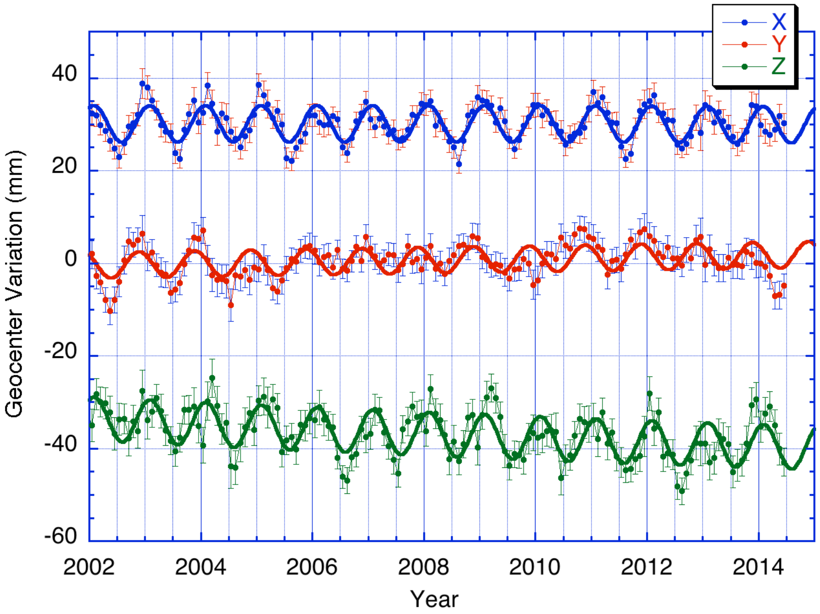

Figure 1. Monthly geocenter variations from SLR to 5 satellites.

The SLR data provide estimates of the geocenter motion that extend back to 1992, providing an opportunity to look for long-term non-linear variations in the geocenter. Figure 2 illustrates a time series of 60-day estimates for the Z geocenter component from the LAGEOS satellites and compares it to the uplift observed by GPS at KELY. There is a considerable correlation between the two. The loss of ice mass loss in Greenland would be reflected by the geocenter moving towards –Z and uplift in the crust. There is clear evidence in both series of the accelerated ice mass loss observed by GRACE, and additional analysis is planned to verify the reliability of this interpretation.

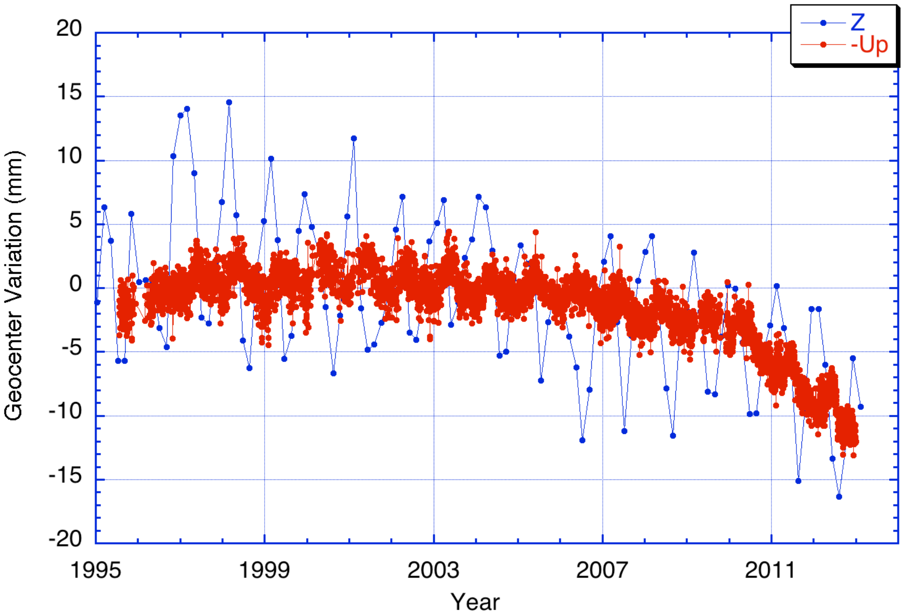

Figure 2. Geocenter variation in Z from SLR compared to uplift at KELY observed by GPS. The uplift has been scaled by -0.2 to make it comparable to the geocenter motion.

Degree-2 gravity variations

The estimates for C20 from GRACE (Figure 3) are corrupted by the appearance of 'tide-like aliases' that are likely the consequence of some twice-per-rev thermal effect in the GRACE observation system (the periodicities are consistent with harmonics of the orbit beta-prime angle). Figure 3 also illustrates the long-term time history of C20 from up to eight SLR satellites. There is a clear increasing departure from the long-term trend expected from Glacial Isostatic Adjustment (GIA), which is almost certainly the consequence of present-day accelerating ice mass loss, as is the non-linear trend in C21 illustrated in Figure 4 (Cheng et al., 2013; Chen et al., 2013).

For some time, it was observed that the estimates of C21 from SLR were inconsistent with GRACE and with the expected value computed from the mean pole (Figure 4). It was found that the contribution to C21 from the mix of 5 satellites led to competing signals from satellites in different orbit inclinations, and the estimation of just two order-1 harmonics was inadequate to accommodate them all. The addition of a third order-1 term (degree 6) provided the necessary degrees of freedom, though the scatter is slightly increased.

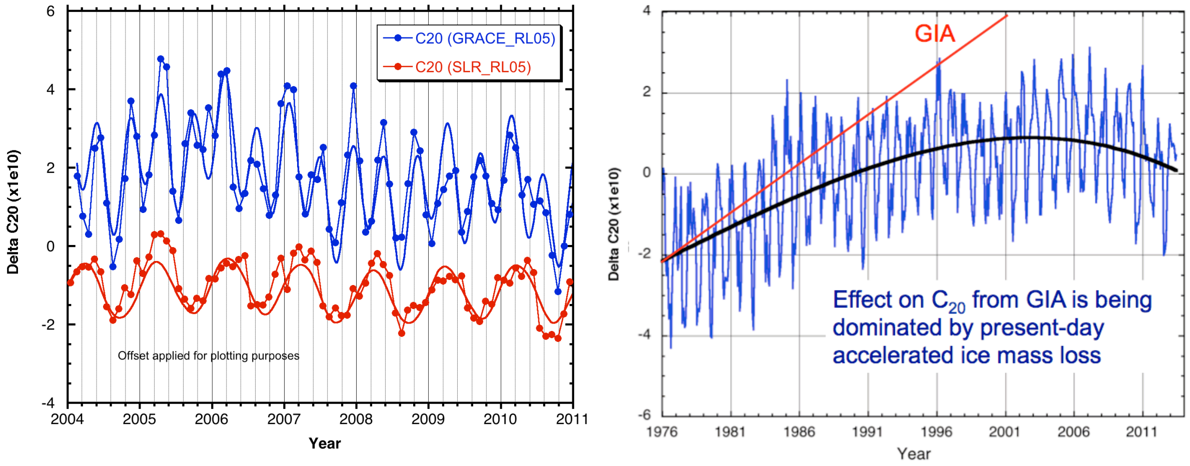

Figure 3. (left) Monthly C20 estimates from GRACE and SLR; (right) Estimates of C20 from SLR dating back to 1976 compared to an estimate of the effect of GIA on C20.

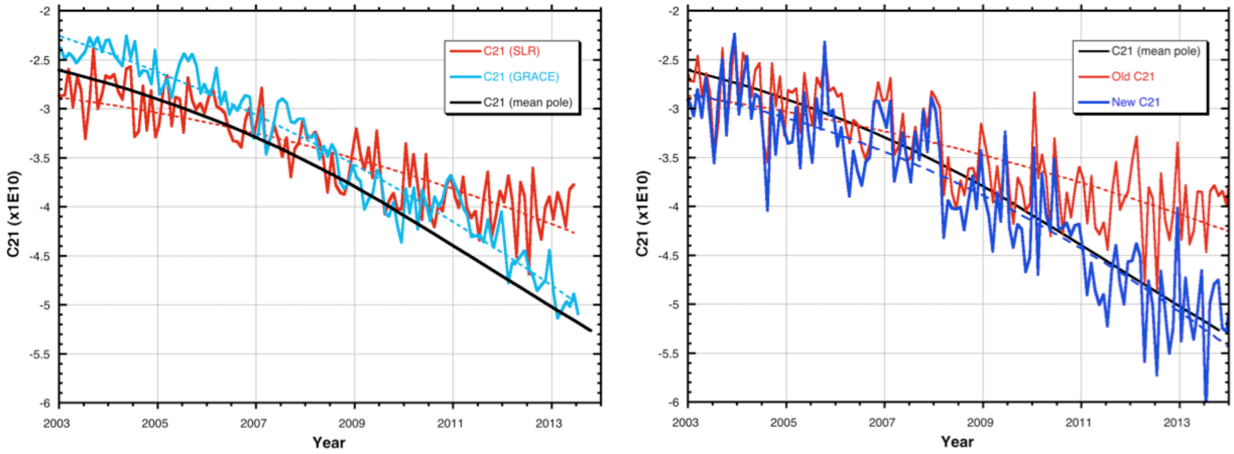

Figure 4. (left) Monthly estimates of C21 from GRACE, SLR and using the mean pole; (right) Monthly estimates of C21 compared with (new) and without (old) estimating C61.

Filling the gap between GRACE and GRACE Follow-on

There is likely to be a gap between GRACE and its follow-on mission scheduled for launch in late 2017. It is considered essential to monitor the larger scale mass variations during that period. A possible strategy would be to extend the resolution available from SLR only (currently to about degree 5) with GPS tracking of one or more satellites with a good accelerometer (including possibly one of the GRACE satellites if still operating). It can be shown that the resolution needed to resolve continental scale signals requires at least a 7x7 gravity field, and of course discrimination of finer scale features requires higher harmonic degrees. The feasibility of a such a solution is illustrated in Figure 5, which shows the correlation between the GRACE RL05 estimates and those obtained from GPS tracking to one GRACE satellite and the same but augmented with SLR tracking to 5 satellites. A significant increase in the correlation is clear, particularly for the zonals. With the launch of the very dense LARES satellite in 2012, we can expect even further improvement in the contribution of the SLR satellites to time variable gravity determination.

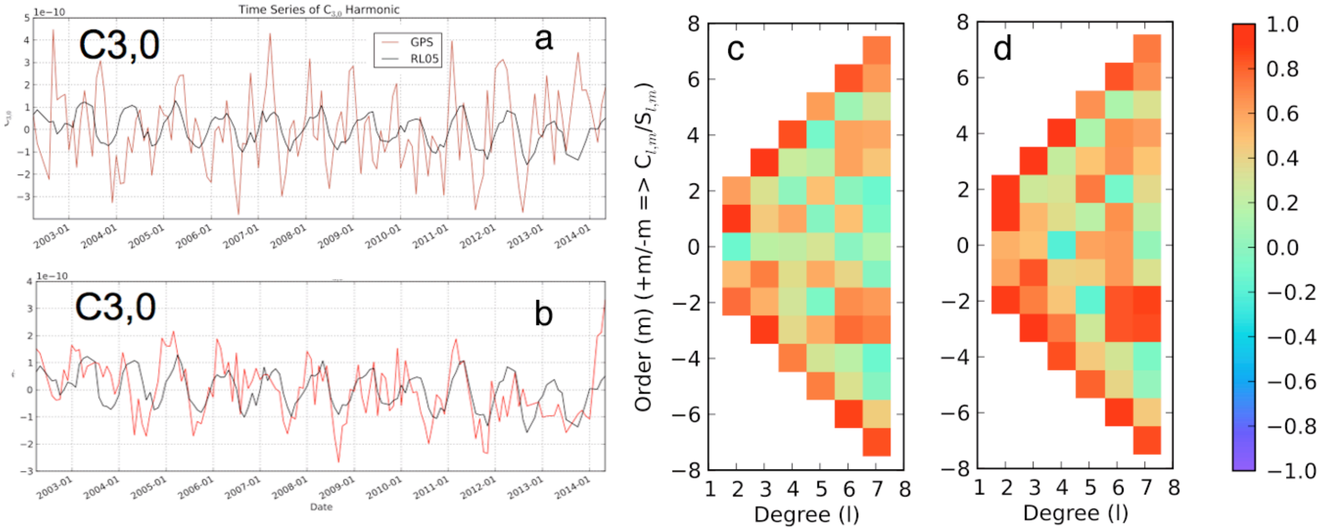

Figure 5. On the left, the monthly estimates of C30 from GRACE RL05 and GRACE GPS without (a) and with SLR (b). On the right, the correlation between GRACE RL05 estimates of a 7x7 gravity field using GRACE GPS without (c) and with SLR (d).

Testing General Relativity

General Relativity (GR) predicts an interesting effect due to the rotation of the Earth's mass; a satellite orbit will be 'dragged' in the direction of rotation and create a drift in the orbit nodal motion. This 'frame-dragging' or Lense-Thirring precession is measurable by SLR, but the uncertainty in the Earth's gravity field, particularly the even zonals, has previously limited the accuracy. With the availability of greatly improved gravity field models from GRACE and the use of both LAGEOS satellites, it is possible to create a combination of the two residual node signals that removes the dominant error from C20 (i.e., J2) (Ciufolini & Pavlis, 2004). Figure 6 illustrates this concept using the GGM03S gravity field and four years of SLR data coincident with the GRACE data used for GGM03S (Ries et al., 2008). The result agrees with GR to ~3%.

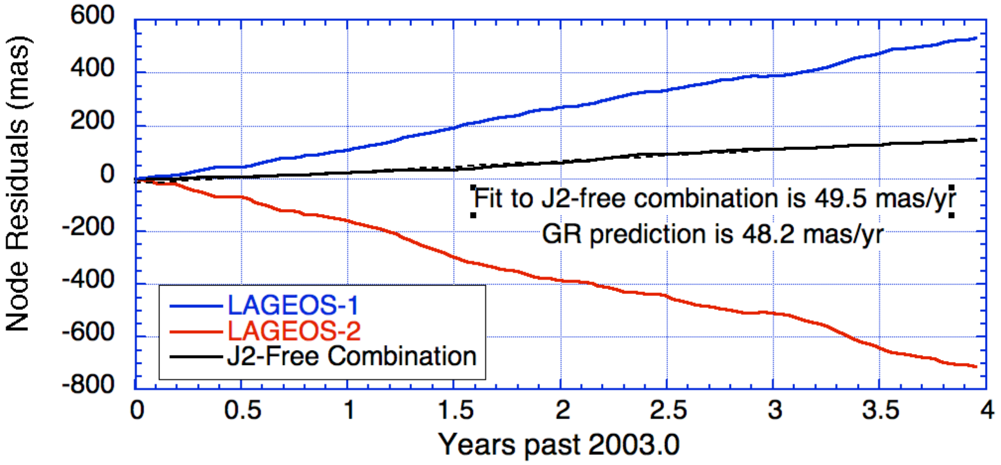

Figure 6. The node residuals for LAGEOS-1 and 2 using the GGM03S gravity model (Lense-Thirring precession not modeled) and the 'J2-free' combination of the two.

Conclusions

In spite of much more data (including a second LAGEOS satellite), more accurate data, and improved models, the estimate of GM has not significantly changed, though the reference frame scale uncertainty due to GM can probably be reduced to ~0.4 ppb. This is significantly smaller than the ~2 ppb uncertainty assigned to the original estimate of GM, not completely negligible when compared to the scale offset between SLR and VLBI of approximately 1 to 1.5 ppb that has persisted in the last several TRF solutions. Reducing the uncertainty in GM requires being able to further refine the confidence range in the CoM model for the LAGEOS satellites. The geocenter variations are an important complement to GRACE, as these degree-1 terms are required to get the total mass transport. The monthly SLR-based estimates for C20 are also essential for GRACE, and this is likely to be true for GRACE FO as well. The source of the tide-like aliases in C20 is thought to be a thermal effect in the GRACE observation system, and GRACE FO will be using the same satellite design. In addition, the long time series of low-degree harmonics help put observations from GRACE into the context of long-term gravity changes. SLR, likely in combination with GPS data from GRACE or other satellites with good accelerometers, will be essential for filling the gap between GRACE missions. Finally, the test of General Relativity will steadily improve, particularly with the addition of the LARES satellite.

Acknowledgements

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References

Chen, J.L., C.R. Wilson, J.C. Ries, and B.D. Tapley, *Rapid ice melting drives Earth's Pole to the east*, Geophys. Res. Lett., 40, 1-6, DOI:10.1002/grl.50552, 2013.

Cheng, M.K., B.D. Tapley, and J.C. Ries, *Deceleration in the Earth's oblateness,* J. Geophys. Res., 118, 1-8, 2013, DOI: 10.1002/jgrb.50058.

Cheng, M.K., B.D. Tapley, and J.C. Ries, *Geocenter variations from analysis of SLR data*, in Reference Frames for Applications in Geosciences, International Association of Geodesy Symposia, Vol. 138, 19-26, 2013.

Ciufolini, I., and E.C. Pavlis, *A confirmation of the general relativistic prediction of the Lense-Thirring effect*, *Nature* 431, 958–960, 2004.

Mendes, V.B., and E.C. Pavlis, *High-accuracy zenith delay prediction at optical wavelengths*, Geophys. Res. Lett., 31, L14602, doi: 10.1029/2004GL020308, 2004.

Ries, J.C., R.J. Eanes, and M.M. Watkins, *Confirming the frame-dragging effect with satellite laser ranging*, 16th International Laser Ranging Workshop, Poznan, Poland, 15-19 October 2008.

Ries, J.C., R.J. Eanes, C.K. Shum, and M.M. Watkins, *Progress in the determination of the gravitational coefficient of the Earth*, Geophys. Res. Lett., 19(6), 529–531, March 20, 1992.

Swenson, S., D. Chambers, and J. Wahr, *Estimating geocenter variations from a combination of GRACE and ocean model output*, J. Geophys. Res., 113, doi: 10.1029/2007JB005338, 2008.