Time-variable gravity from SLR and DORIS tracking

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Abstract

One of the significant strengths of the tracking of satellites with satellite laser ranging (SLR) is the long time base of data available. This has been exploited to provide us with monthly snapshots of the variations of the low-degree field from approximately 1980 to the present. The analysis of these data by Cox and Chao [2002] revealed an anomaly in the zonal rate for J_2*. Cox and Chao [2002] clearly indicated that the contributions to this zonal rate from the cryosphere and surface hydrology, such as glacier melt and ground water storage, are just as important as post-glacial rebound. In this paper, we extend the time series of low degree variations through 2006, describing the satellite data incorporated into the solutions, the method of analysis, and the satellite performance. We compare the SLR/DORIS recovered low-degree variations with those derived from GRACE from 2003 to 2005, through degree four, and investigate the climatological and geophysical connections revealed by the new time series.*

Introduction

Although GRACE provides us with a valuable source of high-resolution data for assessment of surface mass transport, the analysis of SLR and DORIS tracking data to low Earth orbiting satellites still provides valuable information. Intercomparison of the GRACE and independent SLR & DORIS results can provide a validation of the GRACE results where the data overlap after launch of GRACE, and an improvement in the quality of the time series through improvements in the dynamic modeling, for example through usage of the GRACE-derived geopotential. In this manner, the joint analysis of GRACE and the SLR and DORIS tracking data can help to leverage these data into the pre-GRACE era. In this manner we can obtain a snapshot of surface mass transport on the Earth over the past 25 years.

Data and Processing

The gravity solutions are based on data to nine satellites: Lageos 1 & 2, Starlette, Stella, Ajisai, Westpac, GFZ-1, TOPEX/Poseidon, and BE-C. The temporal coverage of the tracking data is depicted in Figure 1. For most of the 1980's, only three satellites are available. From the 1990's onward, between six and nine satellites are used, including the SLR & DORIS tracking data to TOPEX/Poseidon.

The modeling applied the ITRF2000 reference frame [*Altamimi et al.*, 2002] with corrections for certain stations, derived principally by the TOPEX/POD team (N. Zelensky, NASA GSFC, personal communications). The GGM01C GRACE-derived gravity model was used [*Tapley et al.*, 2004]. The IERS2003 solid Earth tides were applied including anelasticity [*McCarthy and Petit*, 2004]. The GOT00.2 T/P-derived ocean tide model was applied [*Ray*, 1999]. The atmospheric gravity was forward modeled using atmospheric pressure data from NCEP to 20x20, with an inverse barometer correction assumed over the oceans. The observed annual gravity terms to 4x4 were forward modeled a priori, based on a previous SLR time series solution. After 1992, the daily arcs are 10 days in length, and constructed to be commensurate with the start and stop times of the near-ten day ground track cycle of TOPEX/Poseidon. Prior to 1992, the arc length was 30 days for Lageos-1, and 15-days for Starlette and Ajisai. For all the arcs, global station biases are adjusted for the SLR data. The gravity solutions consisted of a 30x30 static field, a 6x6 field for the secular rates of the geopotential, annual and semi-annual terms to 4x4, and a 4x4 monthly time series.

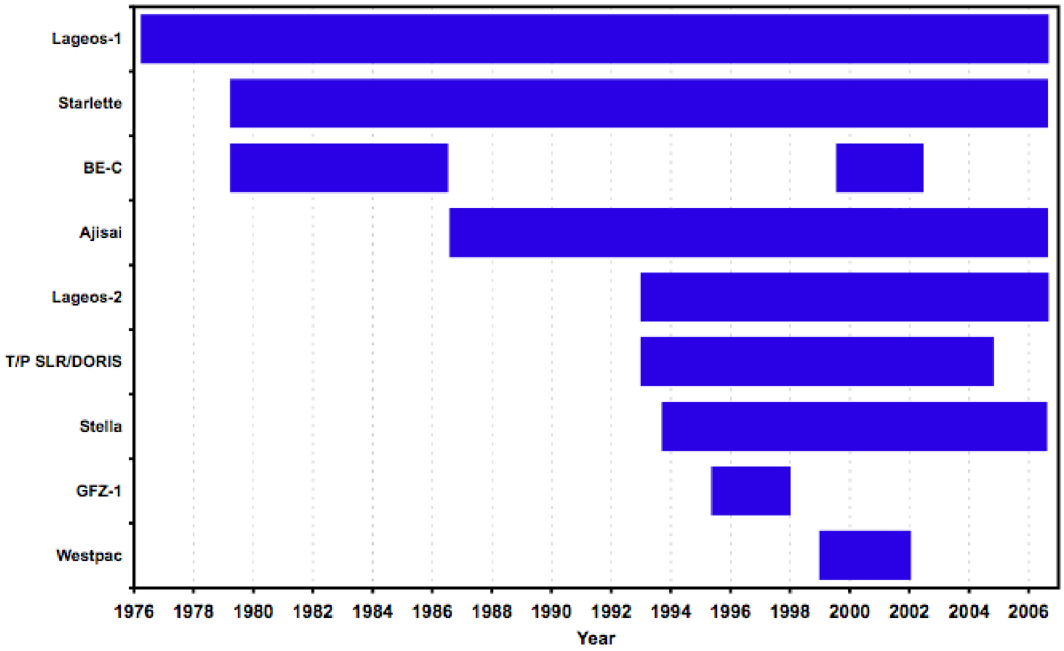

Figure 1. *Temporal coverage of SLR and DORIS tracking data used in the monthly gravity solutions, the solutions for the annual and semi-annual harmonics and the solutions for the secular rates.*

Analysis of the J_2 signal

The full time series is depicted in Figure 2, with respect to the GGM01C. The 1998 J_2 (- C_{20}) anomaly discussed in *Cox and Chao* [2002], appears as an inter-annual variation. The slope in J_2 obtained from 1980 to 1997 of 1.34 x 10^{-11}/year is similar to the post 1997 slope of 1.36 x 10^{-11}/year. It now appears, especially after the application of an annual filter, that a similar interannual variation was observed in 1987-1988. The J_2 time series is visibly much noisier before 1983. The addition of Starlette to the solution, especially after 1983, acts to stabilize the solutions for J_2 and the other low degree harmonics. An additional consideration is that the strength of the network and the quality of the data for 1983 and later is far superior to the pre-1983 SLR data. For reference, we note that a ± 1 x 10^{-10} in J_2 corresponds to a ± 2 mm change for the geoid in a zonal sense from pole to equator.

In Figure 3 we compare the C_{20} time series for GRACE, and from the SLR & DORIS solutions from 2002 to 2006. We show the comparisons for the CSR Release 01 fields (constrained and unconstrained), the NASA GSFC GRACE solutions based solely on GRACE K Band Range-Rate data (KBRR) from *Luthcke et al.* [2006[, and the corresponding SLR & DORIS solution. The unconstrained CSR release 01 (RL01)

C_{20} data have the worst agreement, especially around the period in late 2004 when GRACE entered a deep resonance driven by a close ground track repeat. The solutions lightly constrained by a Kaula constraint are smoother in their performance. The C_{20} from the NASA GSFC spherical harmonic time series is smoother, but still does not have good agreement with the SLR & DORIS solution. We conclude that the GRACE spacecraft are not a good sensor of this very long wavelength harmonic.

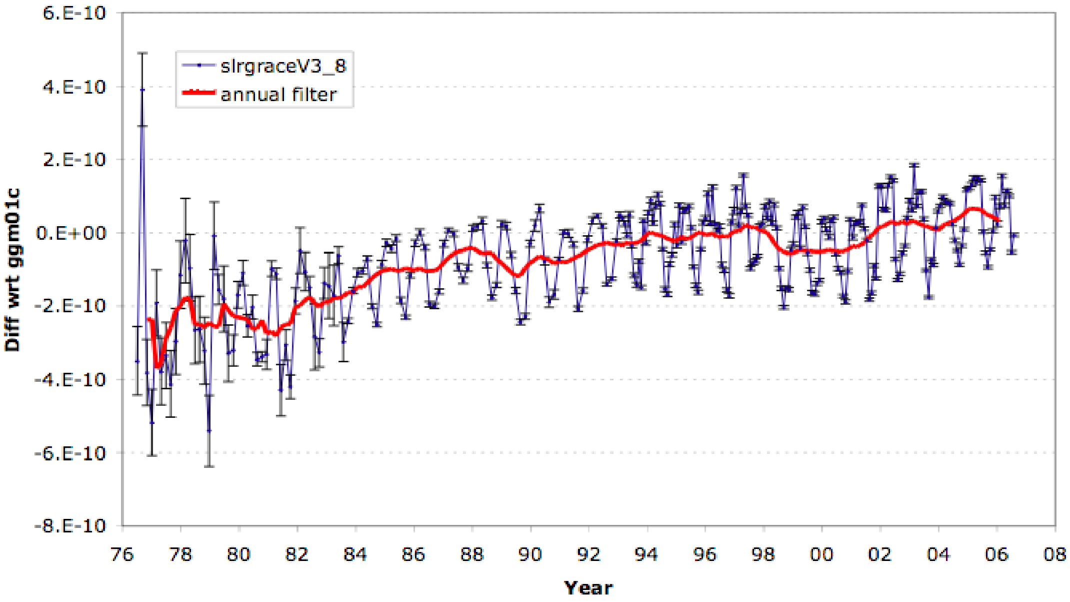

Figure 2. *Monthly J2 solutions from SLR and DORIS tracking from 1976 through 2006. The solutions are shown w.r.t. the GGM01C solution, and with the application of an annual filter (red line).*

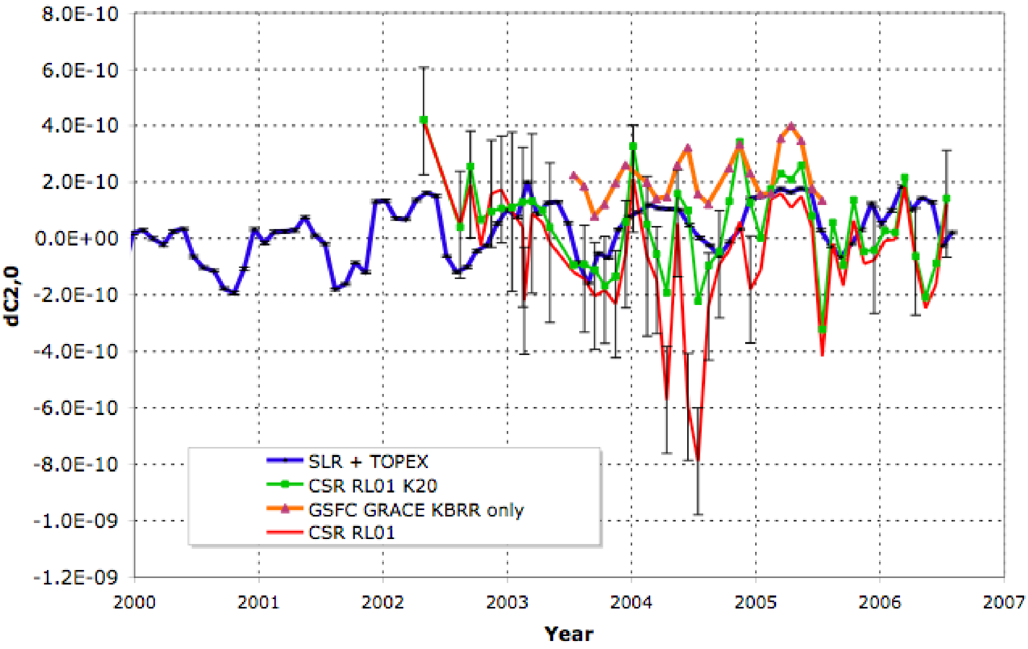

Figure 3. *Comparison of solutions for C_{20} from the SLR and DORIS solutions, and from GRACE.*

Comparison of Other Low Degree Harmonics

The SLR and DORIS monthly time series is compared to the GRACE solutions in Figure 4 for the other low degree harmonics (C_{21}, S_{21}, C_{22}, S_{22}, C_{30} and C_{40}). For C_{21} and S_{22}, the agreement is exceptionally good; For S_{21} and C_{22} there is some agreement on the amplitude of the variation, but the phases really do not match. For C_{30} we obtain the interesting result that the time series for the two GRACE solutions (CSR RL01, and NASA GSFC, KBRR-only) agree perfectly. The SLR and DORIS time series matches more closely the GRACE C_{30} + C_{50} solutions, suggesting that for the C_{30} harmonic, what the SLR and DORIS time series discerns is really a lumped harmonic. In contrast for the C_{40} harmonic, the GRACE solutions completely fail to discern the variations that are visible in the SLR and DORIS time series. We conclude that for C_{40}, just as for C_{20}, the GRACE spacecraft are simply not good sensors of this harmonic.

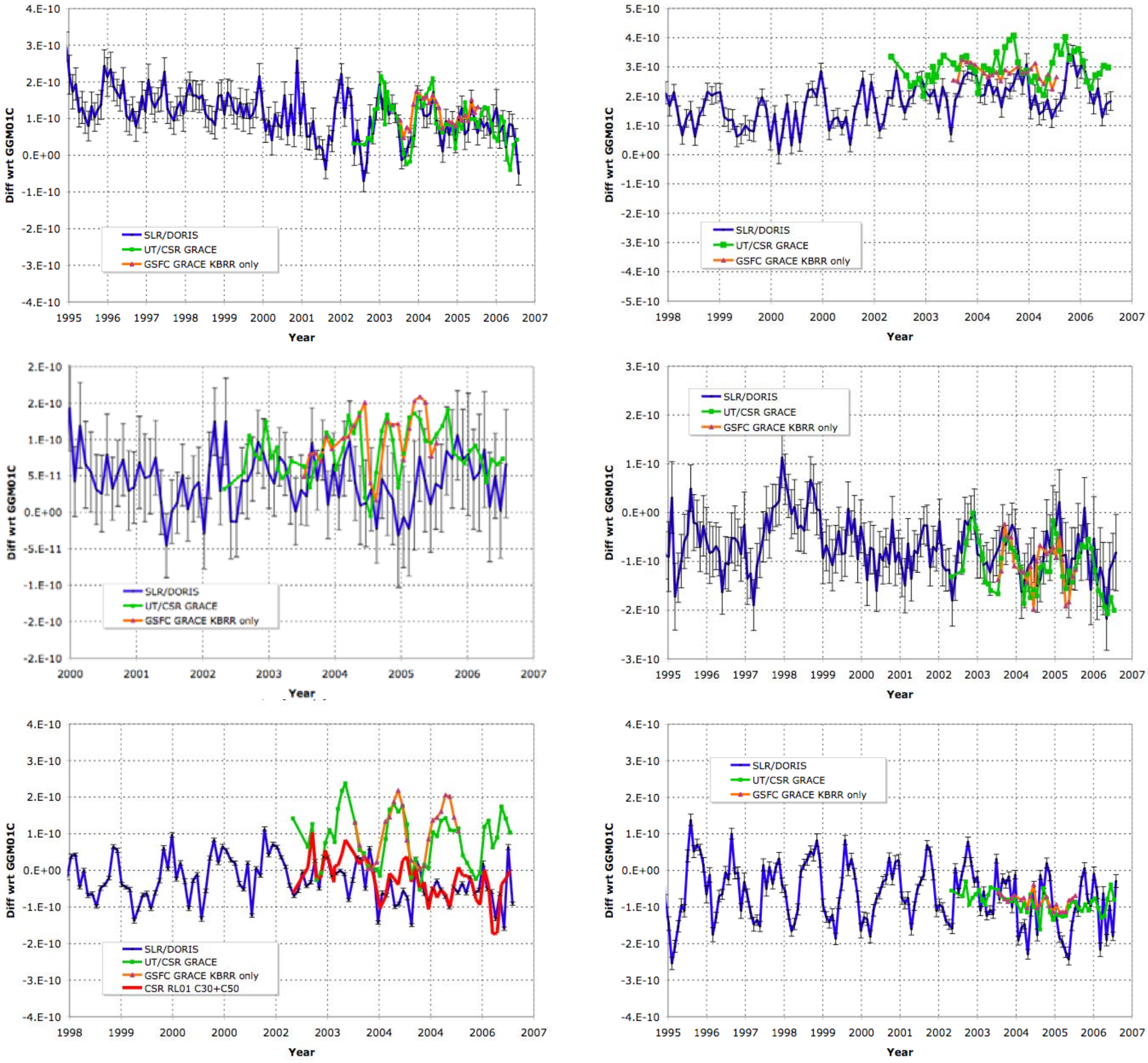

Figure 4. *Comparison time series for the low-degree harmonics between GRACE and the SLR and DORIS solutions (C_{21}, S_{21}; C_{22}, S_{22}; C_{30}, C_{40}). We show the formal errors for the SLR/DORIS solutions. The agreement is exceptionally good for the C21 and S22 harmonics. For the two GRACE solutions tested, the variations in the C40 harmonic cannot be properly resolved.*

Recovery of Annual and Semiannual Harmonics

We are able to use the entire time series of SLR and DORIS data to recover the annual variations in the geopotential through degree six, and the semiannual variations through degree four. In Figure 5, the signal of the annual harmonics recovered from the CSR RL01 GRACE series, is compared to the signal recovered from the SLR & DORIS time series, and the formal uncertainties of the SLR and DORIS recovery. Thus, from this comparison of the degree variances, the SLR and DORIS data can recover signals between degrees five and six.

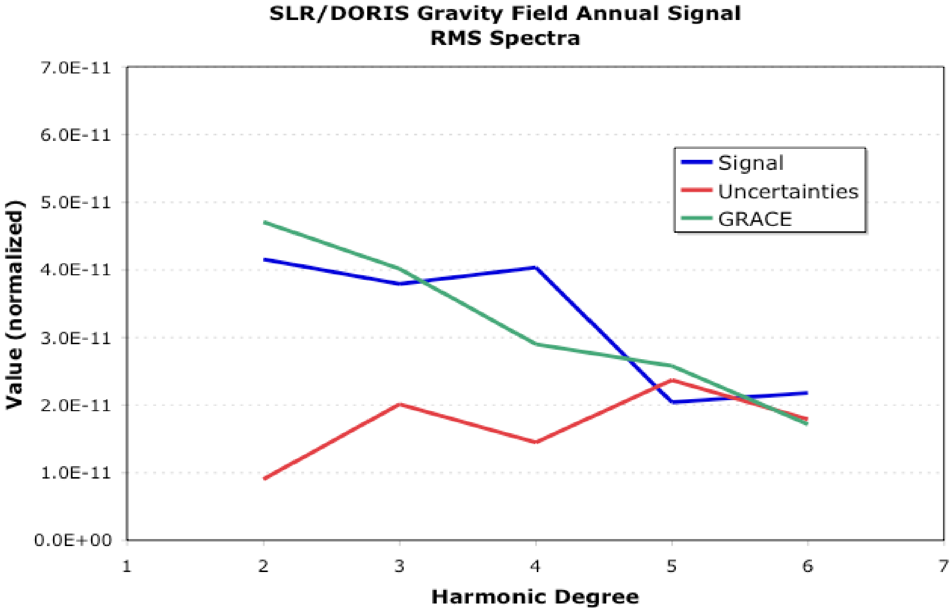

Figure 5. *Degree variances of the annual harmonics recovered from the SLR and DORIS data, and from the GRACE monthly solutions, compared to the formal uncertainties in the SLR/DORIS solutions. The SLR & DORIS time series can resolve the annual variations in the geopotential through degree five over a period of 25 years.*

The SLR/DORIS time series is sufficiently long that we can reliably recover annual and semiannual harmonics over different time scales. For example, if we compare the time-variable gravity variations for two SLR/DORIS solutions (1979-1997, and 1998-2005), we can observe for the most part overall similarities between the solutions. Both show the same patterns of geoid highs and geoid lows in the Amazon region, and Southeast Asia associated with the expected hydrology variations. If we compare the 1998-2005 SLR/DORIS solution to the annual and semiannual harmonics recovered from GRACE (in this case the CSR RL01), both observe the geoid highs in the Amazon in April and May, and the geoid lows in south east Asia and the Bay of Bengal. In addition, both data sets observe the same phase of the Southeast Asia monsoon with a prominent high in August and September over the Bay of Bengal, Bangladesh and the Indian subcontinent. The geoid low observed over the Amazon in November with the GRACE results is more prominent than with the SLR/DORIS observed variations.

Recovery of Secular Geoid Rates

The long time series of SLR and DORIS data allows to solve for secular rates in the geopotential, not just with the zonal harmonics, but for all coefficients through degree six. The recovered geoid rates are illustrated in Figure 6 for the period from 1979 through 1997. In this figure, the general pattern of post-glacial rebound is observed over Antarctica, Greenland and the Arctic consistent with post-glacial rebound models. Globally the scale of the variations is ± 1 mm/year, with an error of 0.14 mm/year. Secular geoid changes occur in other regions, for example over the Indian subcontinent (+0.5 mm/yr). While we may ascribe the secular changes in the polar regions for the most part to changes in the solid Earth (cf. post-glacial rebound), in other regions, other considerations (long-term hydrology or ocean mass variations) may also play a role. If secular solutions are obtained on shorter time scales (five years) the solutions differ considerably, indicating that on those time scales, annual and inter-annual variations in the geopotential are more prominent than the secular variations.

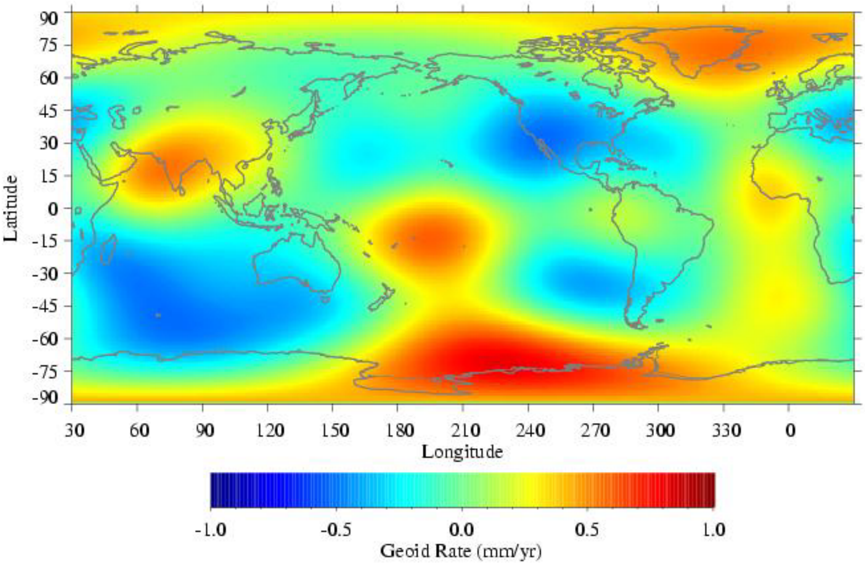

Figure 6. *Geoid rates observed from 1979 through 1997 from SLR and DORIS data. The global error is 0.14 mm/yr.*

Summary

The long time series of SLR and DORIS data allow us to resolve periodic time variations on the time scale of months, and secular variations over the period of many years. These data allow us a window into geophysical mass flux variability over a period prior to the launch of GRACE. We discern that that 1998 C_{20} anomaly was in fact an interannual variation, and that similar variations are observable over the course of the 25-year time series. The GRACE solutions for the low degree even zonals do not agree with those obtained from SLR and DORIS data, although in an overall sense the annual variations observed are similar. The SLR and DORIS data have sufficient strength to resolve secular changes in the geopotential through degree 6 corresponding to a spatial scale of 3300 km.

Acknowledgements

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Wiser Beal1 (Raytheon Corp, Upper Marlboro, MD) performed most of the GEODYN processing for the SLR and DORIS solutions.

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