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Time-Variable Gravity Solutions from 1993-2014 from SLR & DORIS data

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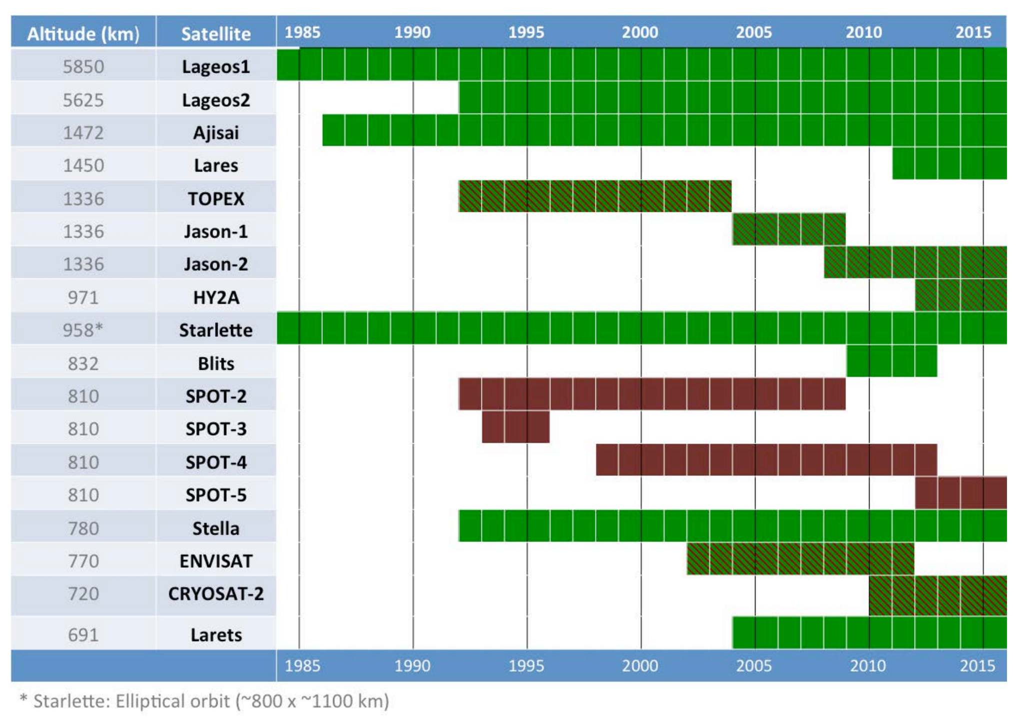
SUMMARY

The GRACE mission has been highly successful in determining the time-variable gravity field of the Earth, producing monthly or even more frequent solutions (cf. 10-day) solutions using both spherical harmonics and mascons. However the GRACE time series only commences in 2002-2003 and a gap of several years may occur in the series before a GRACE follow-on satellite is launched. Satellites tracked by SLR and DORIS have also been used to study time variations in the Earth's gravitational field. In this paper we discuss the development of a new time series of low degree spherical harmonic fields based on the available SLR, DORIS data. We have developed solutions to 5x5 in spherical harmonics based on data from up to 18 satellites tracked with SLR and DORIS data. (i.e. Lageos1, Lageos2, Starlette, Stella, Ajisai, Lares, Blits, Larets, Westpac, TOPEX/Poseidon, Envisat, Cryosat-2, Jason-2, SPOT-2, SPOT-3, SPOT-4 and Etalon1 and Etalon2). The new solutions are consistent with the IERS2010 standards with respect to the mean pole and the definition of C_{21} and S_{21}. We discuss the quality of these solutions, the contribution of the various satellites. We have applied this time series to the computation of orbits for TOPEX/Poseidon, Jason-1, & Jason-2 and to the reprocessing of DORIS data for the NASA GSFC submission to ITRF2013 (series gscwd25 and gscwd26). We discuss the derivation of these solutions and their evaluation, including their comparison with other solutions, such as those derived from GRACE data.

Satellite Data Summary

The SLR and DORIS satellites (**Table 1**) occupy a variety of orbits and inclinations. The cannonball satellites provide the core of the solution, but the satellites tracked by SLR+DORIS provide significant information. The addition of Envisat in 2002 improves the information content of the time series. A disadvantage of this approach is that the solution characteristics will vary with the number of satellites and type of data in the solution.



* Starlette: Elliptical orbit (~800 x ~1100 km)

"Cannonball" satellites (SLR data only)

Lageos1,2 | Starlette & Stella | Ajisai | Larets | LARES

Altimeter ("Box+wing") satellites (SLR +DORIS data)

TOPEX | ENVISAT | Jason 1, Jason-2 | Cryosat-2 | HY-2A

2-channel DORIS receiver (ENVISAT, Jason 1) | DGXX, 8-channel DORIS receiver (Jason-2, Cryosat-2, HY-2A)

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POD Modeling Summary

Table 2: Summary of POD modeling

Arc length: **7-day arcs (**exc. for weeks with satellite maneuvers**)**

Static Gravity: **GOCO2s (GRACE+GOCE model,** Goiginger et al., 2011**).**
Atmospheric Gravity: **ECMWF 6-hr, 50x50.**
Time-Variable Gravity (a priori to 4x4): Harmonic fits to earlier time series solutions.

Stations: **SLRF2008 (SLR) with modified bias modeling; DPOD2008 (DORIS).**

Ocean Tides & Ocean Loading: **GOT4.8**

Solid Earth Tides: **IERS2003**

Mean Pole Model; Background C_{21} S_{21}: **IERS2010**

Non-conservative force modelling: **Satellite-specific (tuned) macromodels, driven by attitude models or where available, quaternion data; Jason-1: UCL model** (Ziebart, 2004). **Envisat: UCL model** (Sibthorpe, 2006).

Parameterization: State vector; where appropriate C_D at suitable temporal frequency; OPR along-track, cross-track/day for macromodel-based satellites; SLR station biases as per SLRF2008 Rosetta Stone, modified after testing on Lageos & TOPEX/Poseidon, Jason satellites; DORIS pass-by-pass range-rate and zenith troposphere biases; DORIS timing bias for SLR+DORIS satellites.

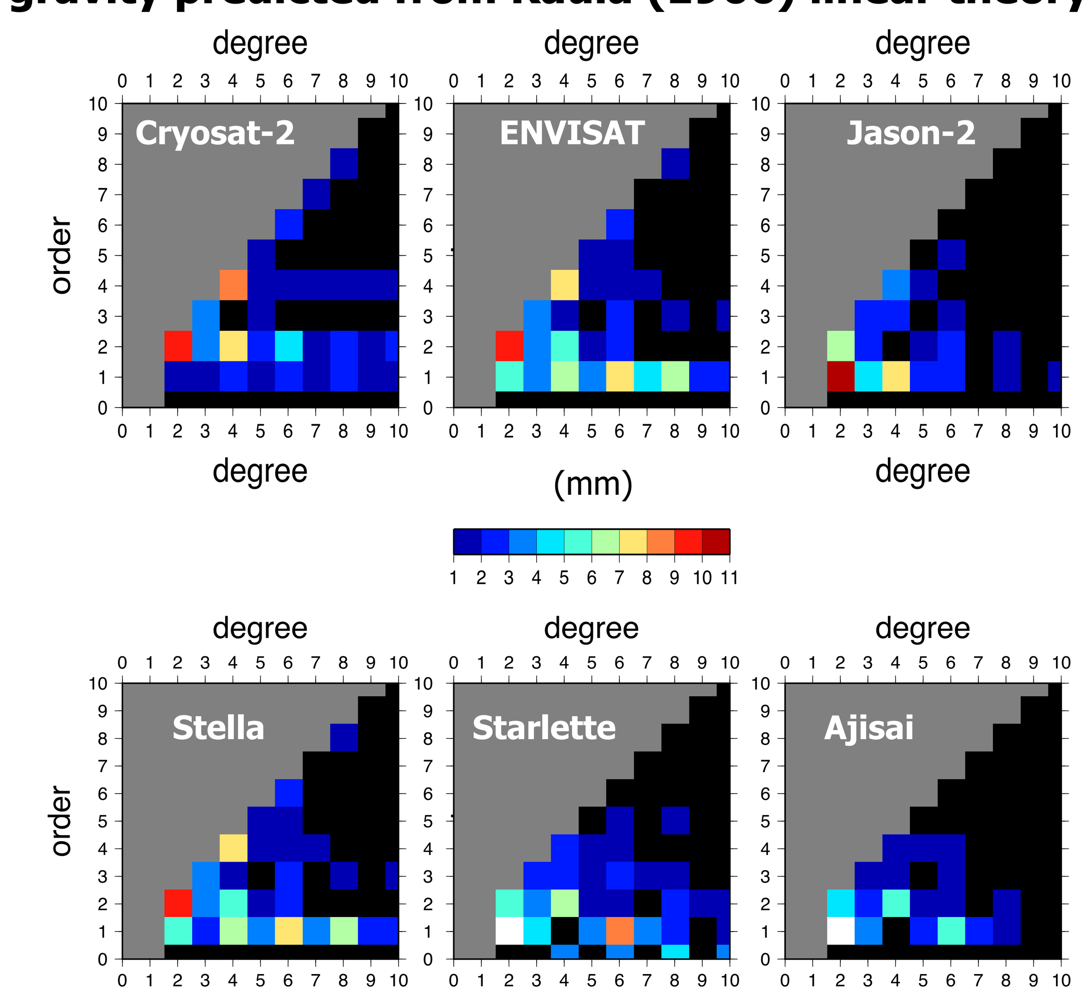
Satellite Sensitivity to T.V.G.

We evaluate the satellite sensitivity to time-variable gravity variations using Kaula's linear theory (Kaula, 1966). We take the GRGS Rl02b gravity models (2006 to 2012), remove the mean, and per week evaluate the predicted radial and along-track perturbations following Rosborough (1986). We present the total RMS sensitivity per coefficient for select satellites. As expected, the sensitivity diminishes for higher degrees, and sensitivity is not uniform across all lower degree coefficients. This analysis considers the m-daily, short period and resonance perturbations. The long-period perturbations affecting the odd zonals are filtered out via a frequency cutoff.

Some salient results for the TVG impact on different satellite orbits.

- Envisat & Stella: C22/S22. ~9 mm; C44/S44 ~7 mm
- Envisat: The satellite has significant sensitivity for terms > L=5 for M=1.
- Starlette and Ajisai. C21/S21. Sensitivity is 16 and 13 mm, respectively.

Satellite perturbations (mm) due to time-variable gravity predicted from Kaula (1966) linear theory



Results

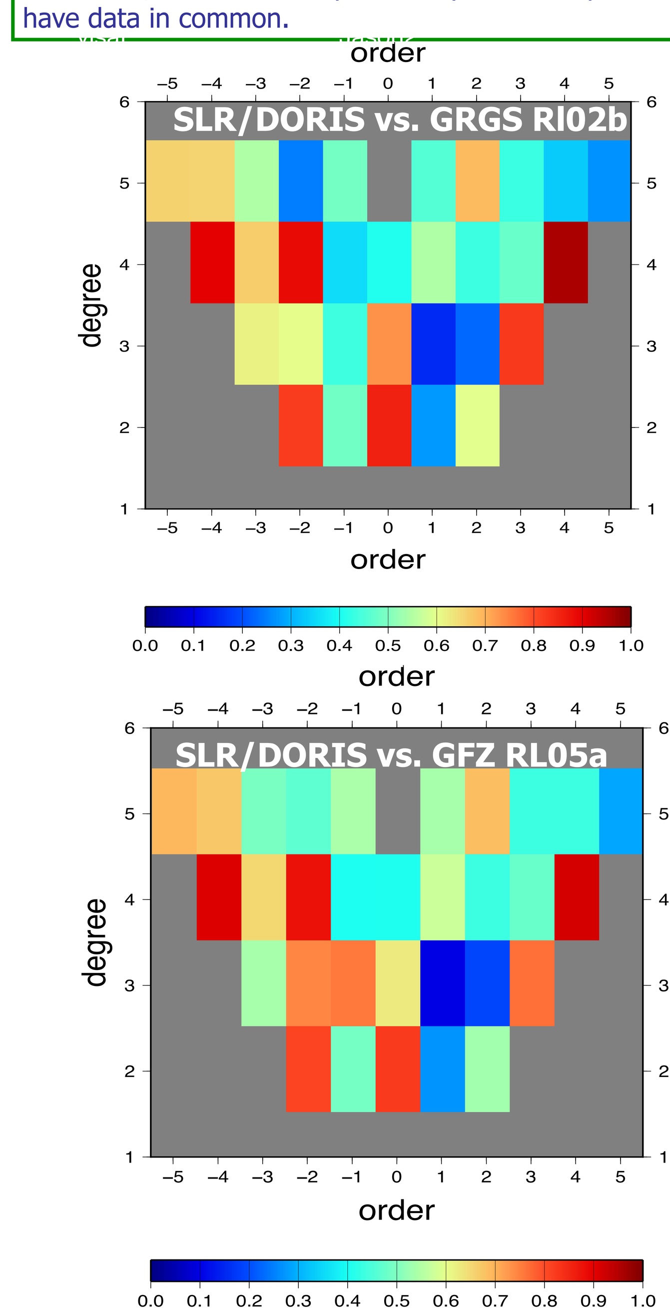
Method of Solution

The normal equations are stacked on a weekly basis and a solution is obtained every seven days from November 1992 to December 2013 using the NASA GSFC SOLVE software, the companion program to the NASA Orbit Determination and Geodetic Parameter Estimation Program (GEODYN). For the Lageos satellites, effectively empirical accelerations are not adjusted, in order to facilitate recovery of the zonals. The weekly solutions are then smoothed using a five week running (boxcar) average. The different satellite normal equations were weighted in a relative sense based on the RMS of fit to the SLR data. A calibration procedure was implemented via the method of Lerch (1991) using subset solutions on a weekly basis, and an average calibration factor was chosen. Five separate series of master solutions and subset solutions were derived before finalizing the solution, which designate via the title "**nominal9c**".

As a comparison, we also derive three "**stacked**" solutions. For these solutions we stack all the normal equations over three time periods: 1993-2003; 2003-2007; 2007-2013, and solve for a constant, rate, annual, and semi-annual to 5x5.

T.V.G. Solution Correlations with external solutions

We compare the SLR/DORIS solutions with external solutions including the GRACE solutions (CSR, GFZ, and GRGS), as well as independent SLR solutions. Each solution is first demeaned and detrended, and then compared only over the period where they have data in common.



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Characteristics of the Solutions

(1) The solutions are by design inhomogeneous in terms of the information content. This is a consequence of the changing number of SLR and DORIS satellites available over the twenty year time span. Hence, the quality and effective resolution of the solution is also variable with time.

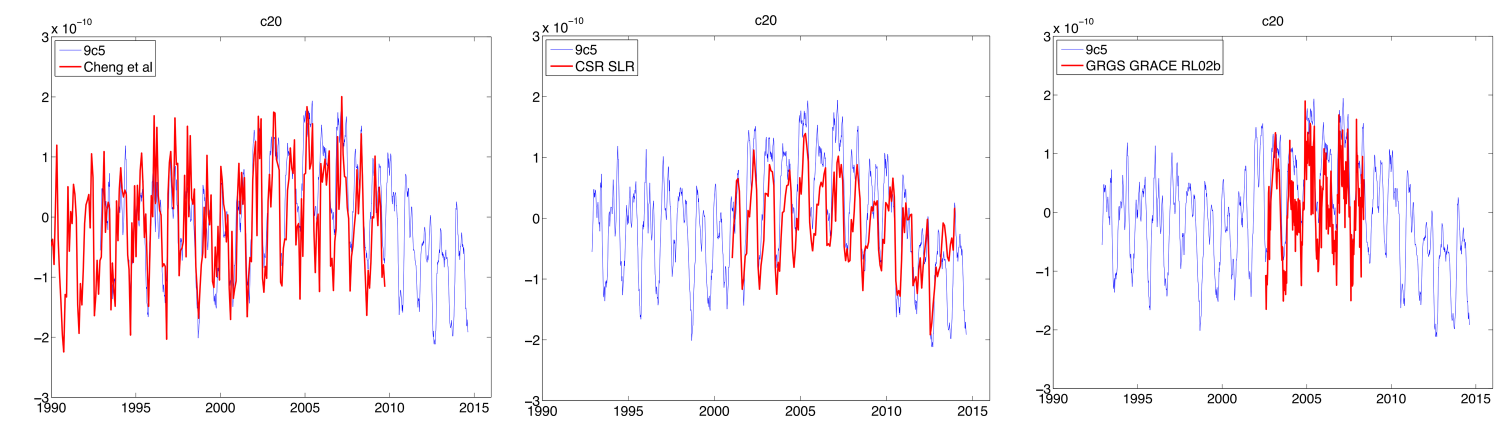
(2) There are two break points in the time series that have a visible impact on the time series: the addition of Stella (October 1993), and the addition of Envisat (June 2002). Polar orbiting satellites (in addition to the Lageos satellites) are important for the stabilization of the solutions for C_{40}; The lower altitude (~800 km), and high quality data from Envisat (SLR & DORIS) positively influence the weekly solutions.

(3) Certain sets of harmonics are at times highly correlated: e.g. C_{20}/C_{40} ;C_{21}/C_{31}; C_{31}/C_{51} ; C_{22}/C_{42};

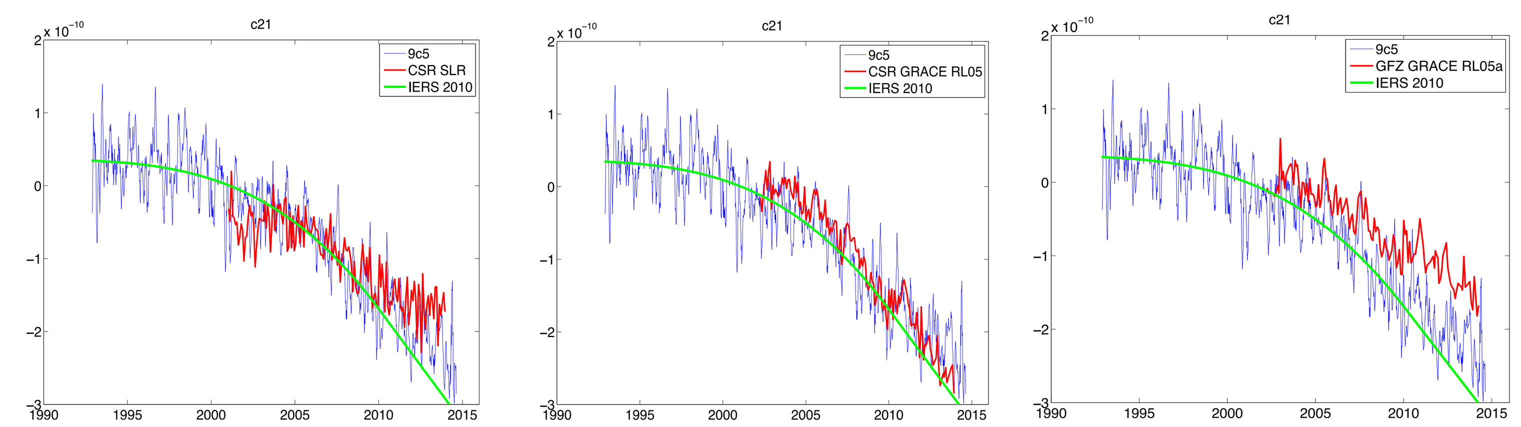
(4) The quality of the solution is highest for degree two, the sectoral terms through degree 4. The C_{31}/S_{31}, C_{51}/S_{51} terms individually seem poorly determined and show unrealistic signals. Possibly the use of once-per-rev terms to mitigate nonconservative force model error, deleteriously affects the recovery for those terms.

Time Series Comparisons w. other solutions

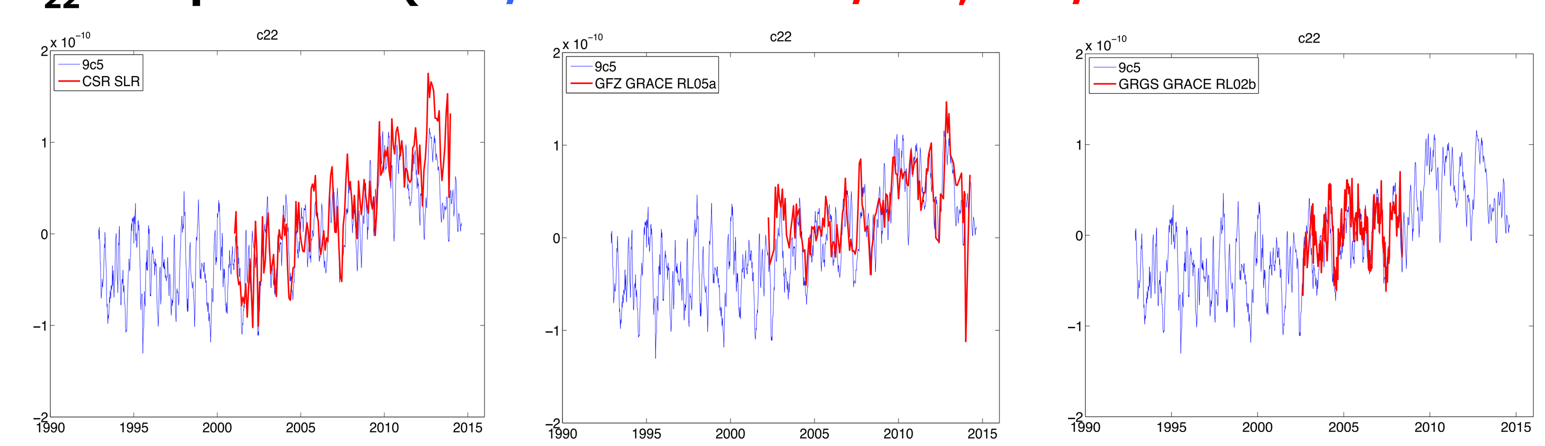
C_{20} Comparisons (SLR/DORIS vs. Cheng et al., CSR/SLR, & GRGS Rl02b)



C_{21} Comparisons (SLR/DORIS vs. CSR/SLR, CSR RL05 GRACE & GFZ/RL05a)



C_{22} Comparisons (SLR/DORIS vs. CSR/SLR, GFZ/RL05a & GRGS Rl02b)



C_{30} Comparisons (SLR/DORIS vs. CSR RL05 GRACE, GFZ/RL05a & GRGS Rl02b)