The Unexpected Signal in GRACE Estimates of C_{20}

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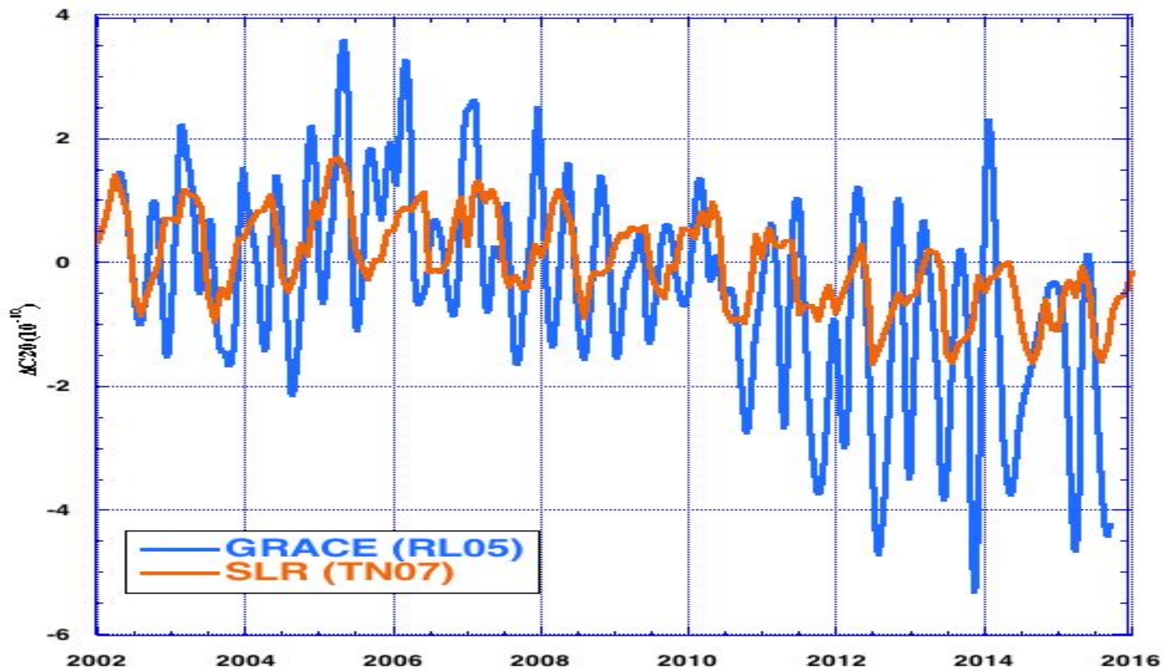

Questions:

What is the cause of the ~160-day signal in GRACE estimates of C_{20}?

C_{20} from SLR is currently used to replace GRACE estimates (GRACE Technical Note 07); Is it reliable? Can it be made better?

References: Cheng, M.K., J. C. Ries (2016) The unexpected signal in GRACE estimates of C20, J. Geod., doi:10.1007/s00190-016-0995-5

Meyrath, T., P. Rebischung, and T. van Dam (2016) GRACE era variability in the Earth's oblateness: A comparison of estimates from six different sources, Geophys. J. Int., DOI: 10.1093/gji/ggw441

S2 tide Aliasing or Something else?

Understanding the cause and origin of the unexpected tide-like signal in C_{20} is necessary for current and future gravity GRACE missions. Particularly, can the 160-day signal be attributed to S2 tidal aliasing?

-- Ocean tide perturbation theory indicates the period of 160-day signal is close to the perturbation period on the GRACE orbits due to the spherical harmonic coefficient pair C_{22}/S_{22} of the S2 ocean tide. This signal appears in the cross-track one-cycle-per-revolution (1-cpr) component of GRACE orbit.

-- A time series of 138 monthly solutions for a 10x10 gravity field along with estimates of selected ocean tide parameters up to degree 6 for the major tides from GRACE GPS data was performed. The signal of ~160 days remained.

-- A signal of ~160-days (half of the beta-prime angle) appears in the cross-track component of the accelerometer (ACC) data and the unreasonably large meridional wind speeds (-100 m/sec) observed with the ACC data might reflect a systematic (likely thermally-induced) variation in the ACC data, which could lead to the unexpected signal of ~160-day in C20.

-- As shown by Mayer-Gürr et al. (2016), that the 160-day anomaly does not appear in the C_{20} time series from ITSG 2016 based on an enhanced accelerometer calibration approach.

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Ocean Tide perturbation on GRACE orbit

The global representation of the ocean tide height

$$\xi(\phi,\lambda,t)=\sum_{S}\sum_{n=1}^{N}\sum_{m=0}^{n}P_{nm}(\sin\phi)\sum_{+}^{-}[C_{snm}^{\pm}\cos(\theta_s+\chi_s\pm m\lambda)+S_{snm}^{\pm}\sin(\theta_s+\chi_s\pm m\lambda)]$$

Ocean tide-induced variations of the geopotential coefficients

$$\Delta C_{nm}-i\ \Delta S_{nm}=F_{nm}\sum_{s(n,m)}\sum_{+}^{-}(C_{snm}^{\pm}\mp S_{snm}^{\pm})e^{\pm i\theta_s} \qquad \theta_s=n_1(\theta_g+\pi-L)+\sum_{j=2}^{6}n_j\beta_j$$

The spectrum of ocean tide perturbations on the satellite orbit

$$\dot{\upsilon}_{slmpq}^{\pm}=\dot{\psi}_{lmpq}\pm\dot{\theta}_s=(l-2p)\dot{\omega}+(i-2p+q)\dot{M}+m(\dot{\Omega}-\dot{\theta}_g)\pm\dot{\theta}_s$$

$$Condition\ of\ long\ period\ perturbation:\ \ l-2p+q=0,\ \ m=n_1$$

$$\dot{\upsilon}_{slmpq}^{+}=(l-2p)\dot{\omega}+m\dot{\Omega}+n_1\dot{L}+\sum_{j=2}^{6}n_j\dot{\beta}_j$$

C_{22}/S_{22} of semi-diurnal ocean tides S2 ($m=n_1=2$): 273.555

$$l=m=2,p=1,q=0\ and\ n_1=2,\ n_2=2,\ n_3=-2,\ n_4=n_5=0$$

$$\dot{\upsilon}_{s2210}^{+}=2\dot{\Omega}+2\dot{L}+2\dot{\beta}_2-3\dot{\beta}_3\ \ \approx 1/160.5$$

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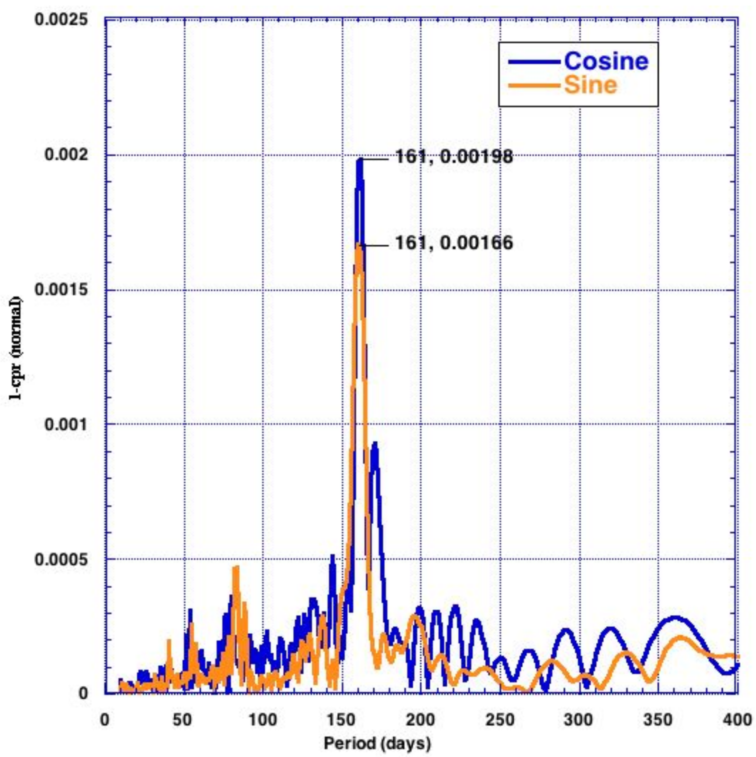
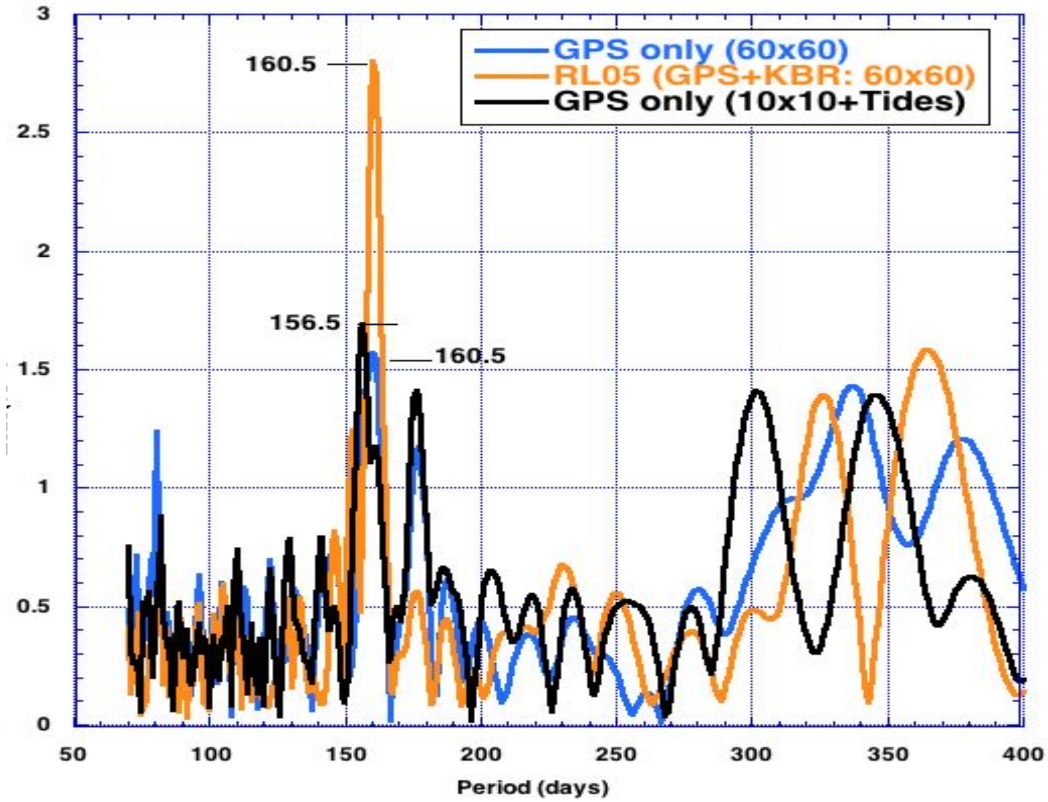
Spectrum of C_{20} variations from GRACE





- The period of the unexpected signal varies slightly depending on what mix of parameters are being estimated; however, the unexpected signal remains even with estimating relevant tides.
- Most of the ocean tide parameters from GRACE are in good agreement (at the mm level) with the ocean tide models.
- The difference in amplitude for degree 2 is only ~3% for O1, 0.2% for M2, 1% for N2, and 6% for S2.

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TN07 SLR estimation of C_{20}

- It is essential that the SLR estimates are as reliable as possible for the wide variety of science applications with replacement values for C_{20}. Particular concerns are (1) higher degree (>5) interaction with the estimates of C_{20} in the SLR solutions; (2) consistency of simply replacing SLR-derived C_{20} estimates with other GRACE-determined gravity coefficients.

- TN07 monthly estimates of C_{20} are from the estimation of the 5x5 (+C_{61}/S_{61}) gravity coefficients and geocenter coordinates based on the monthly SLR data from 5 satellites: LAGEOS-1 and 2, Starlette, Ajisai and Stella.

- The satellite orbits are converged using 3-day arcs with estimated parameters including the satellite state vector (position and velocity) per 3-day arc, 12-hour drag coefficients (Cd) for Starlette, Ajisai and Stella, and daily empirical along-track acceleration (Ct) for LAGEOS-1 and 2. No one-cycle-per-revolution (1-cpr) empirical acceleration parameters were estimated.

- To be consistent for the entire time span and to obtain reliable sigma values, each current monthly solution was estimated with the entire set of previous months (from January 2002) by adjusting a single optimal weighting factor for each satellite for the entire data span. The ranging biases were also estimated in the more recent solutions.

- Test the effects on the TN07 estimates of C_{20} from including C_{60} and/or additional satellites (at different inclinations and altitudes); also assess the rigorous combination of SLR and GRACE.

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Comparison of Variations in C_{20} (normalized)

Case	Rate (10^{-11}/y)	Annual (10^{-11}, deg)	Semi-Annual (10^{-11}, deg)	Cor	Ns	E-C60
TN-07	-1.06	6.74/65	2.88/237	0.41	5	no
SLR-1	-1.07	6.61/61	2.54/231	0.30	6	no
SLR-2	-1.09	6.56/63	2.54/232	0.32	7	no
SLR-3	-1.06	6.67/61	2.56/222	0.44	8	no
SLR-4	-1.94	4.56/71	2.79/243	0.95	5	yes
SLR-5	-0.97	5.51/57	2.12/193	0.87	8	yes
GRACE	-2.36	6.48/46	1.99/337	<0.1	1	yes
SLR+GRACE	-1.90	4.51/61	2.41/245	0.13		yes
DGFI		5.14/43				yes
AIUB	-2.17	4.02/70	3.54/267	0.66	9	yes
ITSG2016	-2.89	4.22/59	4.89/299	N/A	1	yes
CPC	-0.38	6.65/66	1.24/208			

Cor = correlation between C_{20} and C_{40}; Ns = number of satellites; E-C60 = C60 included in estimation

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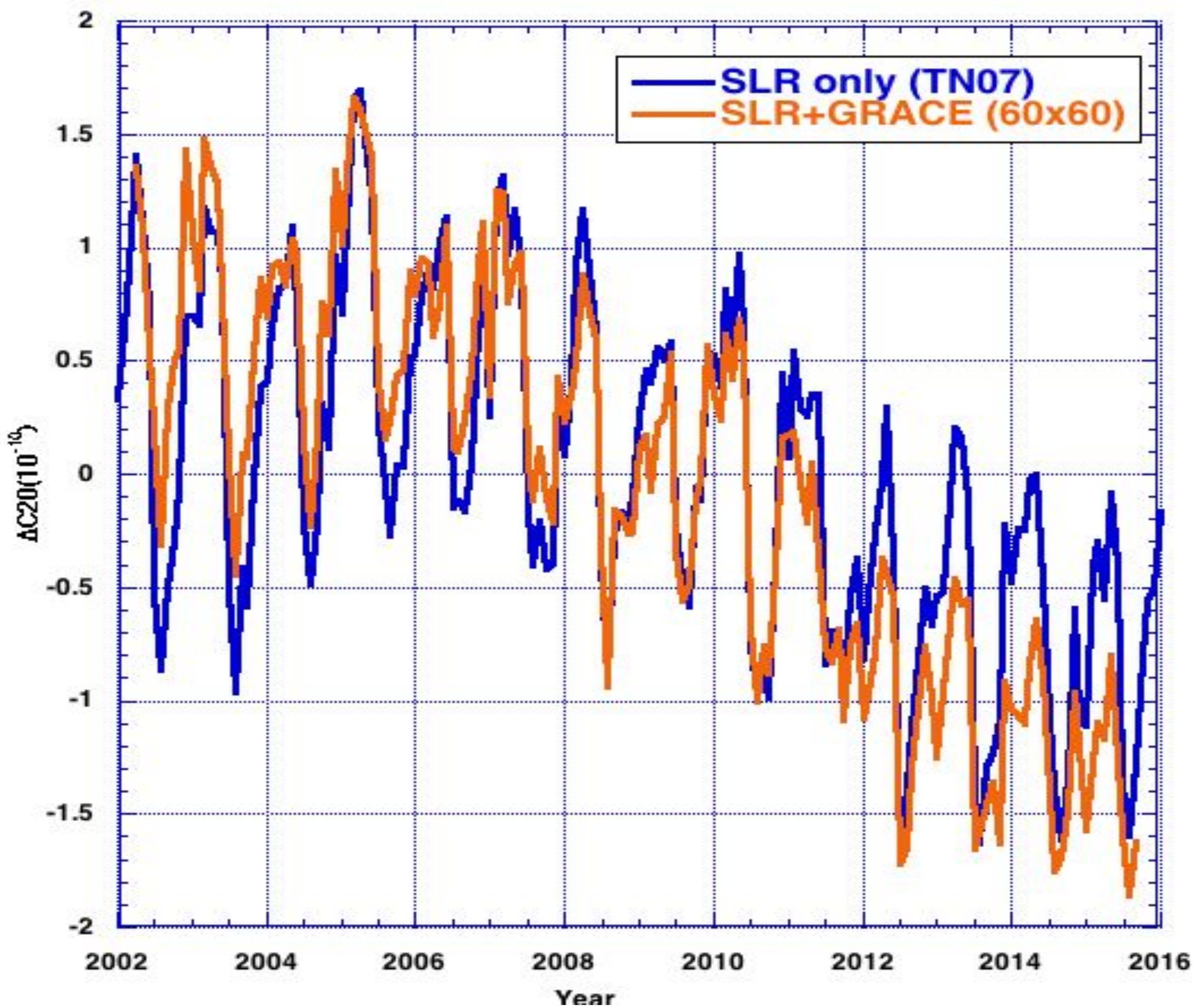
C_{20} from SLR-only (TN07) and SLR+GRACE



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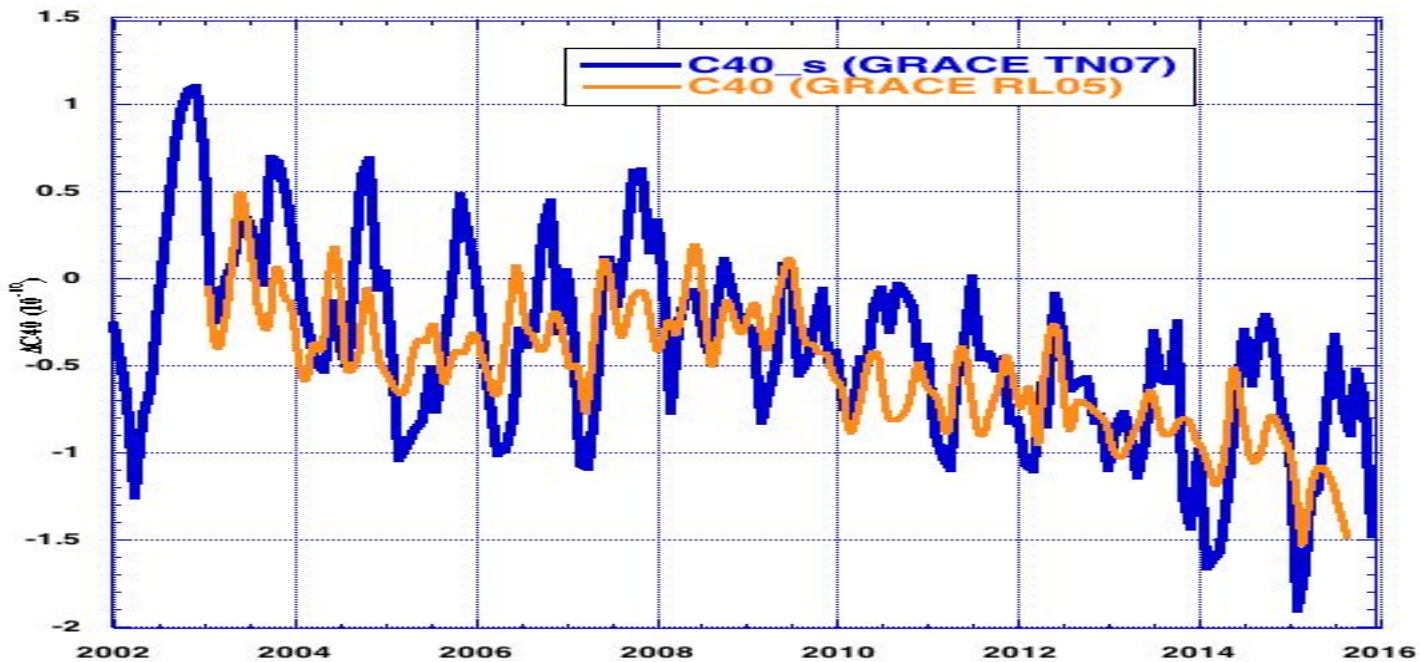
Comparison of Variations in C_{40} (normalized)



Case	Rate (10-11/y)	Annual (10-11,deg)	Semi-Annual (10-11,deg)
TN-07	-0.86	4.12/257	1.66/286
SLR-3	-0.66	4.73/234	2.11/277
GRACE	-0.67	0.95/195	1.73/280
CPC	-0.05	6.41/249	0.28/145

Summary

- The ~160 day signal in C_{20} appears in both the RL05 GPS+KBR and the GRACE GPS-only solutions; suggests a common source of error (such as ACC)
- The ~160-day fluctuation in C_{20} does not disappear with the simultaneous adjustment of a set of global diurnal and semi-diurnal ocean tide parameters.
  - Conclusion: theoretically and practically, the ~160-day fluctuation in C_{20} cannot be attributed to S2 tide model error aliasing.
- Analysis of the cross-track component of the ACC data suggests that a (presumably temperature-dependent) systematic error in the accelerometer data could be a cause.
  - In fact, the 160-day signal does not appear in the C_{20} time series of ITSG_GRACE 2016, which uses an enhanced calibration approach for the ACC data [Mayer-Gürr et al., 2016].
- Existing satellite data are insufficient for separating the gravity coefficients with higher degree and order (>5) in a monthly interval.
  - It is best to maintain the solution of a 5x5 (+C_{61}/S_{61}) field from the current mix of satellites to provide a consistent augmentation for the current GRACE mission.
- Results suggest a poorer recovery of C_{40} by GRACE, where the annual variation is significantly underestimated.
  - Consequently, it appears appropriate to continue to use the SLR-based estimates of C_{20}, and possibly also C_{40}, to augment the existing GRACE mission.

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