J2: An evaluation of new estimates from GPS, GRACE, and load models compared to SLR

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[1] Changes in J2, resulting from past and present changes in Earth's climate, are traditionally observed by Satellite Laser ranging (SLR). Assuming an elastic Earth, it is possible to infer changes in J2 from changes in Earth's shape observed by GPS. We compare estimates of non-secular J2 changes from GPS, SLR, GRACE, and a load model. The GPS and SLR annual signals agree but are different (16%) to the load model. Subtraction of the load model removes the annual variation from GPS, SLR, and GRACE, and the semi-annual variation in GPS. The GPS and SLR long-term signals are highly correlated, but GPS is better correlated with the loading model. Subtraction of the load model removes the 1998 anomaly from the GPS J2 series but not completely from the SLR J2 series, suggesting that the SLR anomaly may not be entirely due to mass re-distribution as has been presumed. **Citation:** Lavallée, D. A., P. Moore, P. J. Clarke, E. J. Petrie, T. van Dam, and M. A. King (2010), J2: An evaluation of new estimates from GPS, GRACE, and load models compared to SLR, *Geophys. Res. Lett.*, *37*, L22403, doi:10.1029/2010GL045229.

1. Introduction

[2] Variations in the Earth's dynamic oblateness (J_2) have been observed by Satellite Laser ranging (SLR) for over 3 decades [*Cheng and Tapley*, 2004; *Cox and Chao*, 2002]. Much of the mass redistribution driving this variation is caused by long and short term climatic forcings. Thus, SLR observed changes in J_2 have attracted considerable attention, particularly the anomalous reversal in trend starting 1998, the so called "1998 anomaly"[*Chao et al.*, 2003; *Cheng and Tapley*, 2004; *Cox and Chao*, 2002; *Dickey et al.*, 2002]. While previous work is based almost entirely on SLR data, this decade new developments are finally providing independent space-geodetic observations of J_2 including the Gravity Recovery and Climate Experiment (GRACE) [*Tapley et al.*, 2004], and also the use of indirect techniques such as Earth rotation [*Chen and Wilson*, 2003] and GPS [*Gross et al.*, 2004]. The premise of indirect techniques is that large-scale redistribution of surface mass causes temporal variations in the Earth's gravity field, rotation and shape which can be linked through an elastic Earth model. Here we present and compare separate estimates of J_2 based on recently and homogeneously reprocessed GPS and SLR data, GRACE, and a model incorporating hydrologic, oceanic and atmospheric loading.

2. Background and Methodology

[3] Expressed as a spherical harmonic expansion, the contribution of the surface mass load $T(\Omega)$ to geopotential $V(\Omega)$ and Earth surface displacements is [*Farrell*, 1972]:

$$V(\Omega) = \sum_{n=1}^{\bar{n}} \sum_{m=0}^{n} \sum_{\Phi}^{\{C,S\}} V_{nm}^{\Phi} Y_{nm}^{\Phi}(\Omega) = \frac{3\rho_S}{a\rho_E} \sum_{n=1}^{\bar{n}} \sum_{m=0}^{n} \sum_{\Phi}^{\{C,S\}} \frac{(1+k_n')}{(2n+1)} T_{nm}^{\Phi} Y_{nm}^{\Phi}(\Omega) \quad (1)$$

$$H(\Omega) = \frac{3\rho_S}{\rho_E} \sum_{n=1}^{\bar{n}} \sum_{m=0}^{n} \sum_{\Phi}^{\{C,S\}} \frac{h_n'}{(2n+1)} T_{nm}^{\Phi} Y_{nm}^{\Phi}(\Omega) \quad (2)$$

$$L(\Omega) = \frac{3\rho_S}{\rho_E} \sum_{n=1}^{\bar{n}} \sum_{m=0}^{n} \sum_{\Phi}^{\{C,S\}} \frac{l_n'}{(2n+1)} T_{nm}^{\Phi} Y_{nm}^{\Phi}(\Omega) \quad (3)$$

where $H(\Omega)$ and $L(\Omega)$ are height and lateral surface displacements, and $Y_{\mathrm{nm}}^{\Phi}(\Phi)$ are spherical harmonic functions. Here we use the notation and normalization conventions of *Clarke et al.* [2007] where a = 6371 km is the mean radius of the Earth, ρ_s = 1025 kg m^{-3} is the density of seawater and ρ_e = 5514 kg m^{-3} is the mean density of the Earth. The quantities on the left hand side of equations (1)–(3) are observable with varying sensitivity by different satellite techniques. The quantities can be related to the load, to each other and consequently to $J_2 = -\sqrt{5}V_{20}^C$ via the elastic load Love numbers k'_n, h'_n and l'_n.

[4] To compare GPS, SLR and load model estimates, weekly load estimates centered on the GPS week are acquired for the 13 year period 1995.0–2008.0 (GPS weeks 782–1459). Geodetic techniques see only the effects of the total load, so we estimate $V(\Omega)$ directly from the satellite equations of motion for SLR and the spherical harmonic coefficients T_{nm}^{Φ} of the surface mass load $T(\Omega)$ from GPS coordinate series using equations (2) and (3). The SLR processing approach is based on the work by *Moore et al.* [2005] but here we use only LAGEOS 1&2. The daily GPS processing is described in detail by *Petrie et al.* [2010]. Daily global fiducial-free GPS coordinate solutions were estimated, and then combined to produce weekly GPS solutions which were subsequently combined, estimating site velocity, offsets due to earthquakes and equipment changes, and rejecting outliers. The site displacement model (velocity

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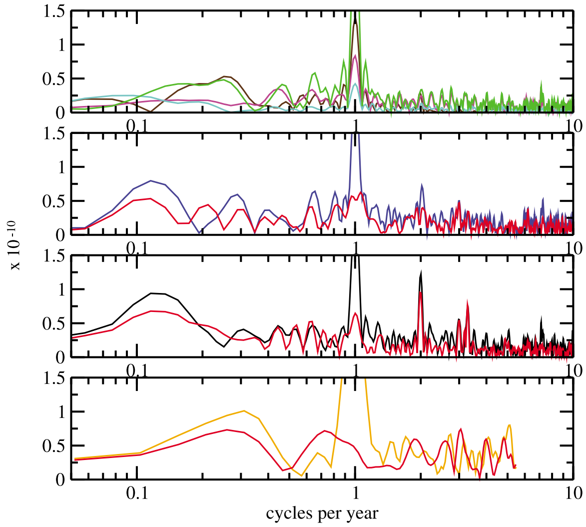

Figure 1. J_2 amplitude spectra, (top) load model (green), land hydrology (brown), atmosphere (magenta) and ocean (cyan). (middle and bottom) GPS (blue), SLR (Black) and GRACE (Orange), red lines are amplitude spectra of the GPS minus load model, SLR minus load model and GRACE minus load model J_2 series.

& offsets) is subtracted from the weekly solutions giving observations of non-secular site displacement. To estimate the surface load from GPS site displacements, we substitute a set of modified basis functions $B^{\Phi}_{nm}(\Omega)$ for $Y^{\Phi}_{nm}(\Omega)$ into equations (2) and (3) [*Clarke et al.*, 2007]. After estimation, the coefficients of the modified basis functions are converted back into spherical harmonic coefficients of the load to compute J_2. The modified basis functions incorporate land-ocean distribution, mass conservation, and self equilibration of the oceans, give a precise and accurate fit in tests using synthetic data and are less subject to aliasing errors [*Clarke et al.*, 2007].

[5] Because a site velocity is estimated to remove tectonic motion and post-glacial rebound from the GPS time series, the estimated J_2 series is entirely non-secular. A secular rate is also estimated and removed from the SLR, GRACE and load model J_2 series. Since tidal variation at 21 years is known to exist [*Cheng and Tapley*, 2004], a time span longer than the 13 years of data used here, it is extremely important that we compare GPS and SLR over the exact same time period and that the subtracted trends are also estimated over the same time period.

[6] Load model coefficients are calculated by summing model contributions of continental, atmospheric and ocean water storage from NASA's Global Land Data Assimilation System (GLDAS) [*Rodell*, 2004], the National Center for Environmental Prediction (NCEP) reanalysis model [*Kalnay et al.*, 1996] and ECCO (Estimating the Circulation and Climate of the Ocean) [*Stammer et al.*, 1999] respectively. We mask out the GLDAS snow water equivalent over Arctic glaciers as they are not reliably modelled. We also add a passive sea level component that enforces mass conservation and an equipotential ocean surface [*Clarke et al.*, 2005], this enlarges our load model J_2 annual by 9%.

[7] For the period 2003–2008 we also include GRACE results from the DMT-1 solution [*Liu et al.*, 2010]. GRACE results are computed relative to high resolution temporal ocean and atmosphere de-aliasing products. To obtain GRACE results that are comparable to GPS and SLR J_2, we add the de-aliasing products back so that the GRACE results reflect the total load.

3. Results

[8] Driven by the expected mass-redistribution signal we use amplitude spectra (Figure 1), to identify the frequency content of the load model J_2 series. We then estimate the amplitude and phase of a six-component frequency model (Table 1) and apply this model to the geodetic J_2 series; significant technique specific frequencies identified in the GPS and SLR spectra are also estimated. The noise level is highest for GRACE followed by SLR, GPS and then load model.

3.1. Annual Signal

[9] The dominant signal in the load model J_2 is annual. It is significant in the spectra of all three load model components (Figure 1). Our annual J_2 amplitude from GPS is 2.38×10^{-10}. The SLR annual is 2.31×10^{-10}, only 3% different to GPS. The load model gives 2.76×10^{-10}, and GRACE 2.60×10^{-10}. All phases agree within error. We conclude that the GPS and SLR agree within error and that the load model annual signal is significantly larger (16%) than GPS/SLR. This assumes that random errors in the load model are comparable to GPS/SLR formal errors. *Cheng and Tapley* [2004] suggest that J2 annual variation is driven by extra-tropical hydrological variation, thus the 16% difference in annual could be caused by deficiencies in the load model in polar areas. We masked out the GLDAS snow water equivalent over Arctic glaciers as they are not reliably modelled, although surface runoff will be captured. Any contribution of Antarctica is also not present in our load model. The majority of previous SLR analyses give higher values: 3.2×10^{-10} [*Cox and Chao*, 2002], 2.78×10^{-10}

Table 1. Estimated Frequency Model Amplitude (A) $\times 10^{-10}$ and Phase (Φ) in Degrees[a]

$^1/_f$ (Years)	f (Cycles/yr)	Model	GPS	SLR	GRACE
		A			
1.00	1.00	2.76	2.38	2.31	2.66
0.50	2.00	0.33	0.77	1.29	0.5
5.77	0.17	0.43	0.48	0.59	
3.99	0.25	0.43	0.56	0.29	0.91
2.26	0.44	0.41	0.27	0.44	0.4
1.57	0.64	0.35	0.49	0.39	0.23
1.24	0.81		0.33		
0.30	3.29			0.61	
		Φ			
1.00	1.00	230	226	233	215
0.50	2.00	128	119	163	234
5.77	0.17	209	56	352	
3.99	0.25	282	357	304	128
2.26	0.44	82	302	288	99
1.57	0.64	11	354	335	166
1.24	0.81		118		
0.30	3.29			207	

[a]Phase is defined by $A\cos[2\pi(t - t_0) - \Phi]$, where t_0 is 1st January. Typical amplitude formal errors σ_A are: 0.08 (GPS), 0.01 (SLR), and 0.06 (GRACE), phase formal errors σ_Φ (in radians) are given by $\frac{\sigma_A}{A}$. Technique specific frequencies are given at 0.30 and 1.24 $1/f$.

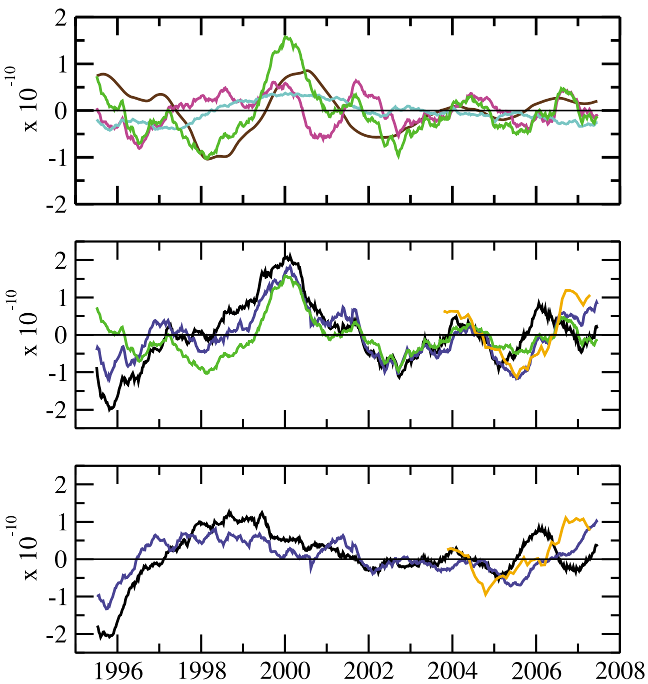

Figure 2. J_2 series after smoothing with a 52 week (12 months for GRACE) running average. (top) Load model (green), land hydrology (brown), atmosphere (magenta) and ocean (cyan). (middle) GPS (blue), SLR (black), GRACE (orange) and load model (green). (bottom) GPS (blue), SLR (black) and GRACE (orange) minus load model.

[*Cheng and Tapley*, 1999], 2.9×10^{-10} [*Cheng and Tapley*, 2004], 3.09×10^{-10} [*Chen and Wilson*, 2008], 2.46×10^{-10} [*Chen et al.*, 2000]. Lower values have also been published: 1.61×10^{-10} [*Moore et al.*, 2005]. It is unlikely that the amplitude of the seasonal cycle remains constant year-to-year. Rather, the estimated annual signal is an average value for the time period considered. Other SLR estimates use longer time periods than the 13 years used here. The difference in time span is the most likely reason for the difference between our GPS/SLR values and other published estimates based on GRACE or SLR. Our GPS, SLR and load model series extend over the same time period, so departure of the load model from GPS/SLR is more notable than the difference from other published SLR results and GRACE. We subtract the load model from the GPS, SLR and GRACE J_2 and compute amplitude spectra (Figure 1). The load model removes the annual peak in all three series.

3.2. Semi-annual Signal

[10] A significant semi-annual periodicity is evident in the GPS and SLR J_2 series but not in the load model. When examining individual hydrologic components (Figure 1), we see a significant spectral peak for land hydrology but not for ocean or atmosphere. A significant or prominent semi-annual peak is not observed in our GRACE amplitude spectra (Figure 1) and subtracting the load model increases the GRACE semi-annual amplitude. The semi-annual amplitudes are 0.77×10^{-10}, 1.29×10^{-10}, 0.5×10^{-10} and 0.33×10^{-10} from GPS, SLR, GRACE and load model respectively. We therefore do not see close agreement between the estimates of semi-annual amplitude; phases are also outside error bounds (Table 1). Notably, the SLR semi-annual amplitude is 1.6–3.9 times the size of the other estimates. Subtracting the load model removes the significant semi-annual peak from GPS but a significant semi-annual peak remains for SLR. Other analyses estimate widely varying SLR semi-annual amplitudes of: 1.25×10^{-10}, [*Cheng and Tapley*, 1999], 0.90×10^{-10} [*Chen and Wilson*, 2003], 0.54×10^{-10} [*Chen and Wilson*, 2008] and 0.83×10^{-10} [*Moore et al.*, 2005]. It is therefore not clear if the large SLR semi-annual is specific to this SLR analysis or SLR observations in general.

3.3. Technique Specific Error

[11] Unexplained technique specific frequencies are seen in both GPS and SLR at 1.24 and 0.3 year periods respectively. GPS error is expected at or very near to the annual and semi-annual frequencies; a number of possible sources for such GPS signals have been identified, e.g., tidal aliasing [*Penna and Stewart*, 2003] and solar radiation pressure mismodelling [*Ray et al.*, 2008]. Such error sources could account for the residual near-annual amplitude seen in the GPS minus load model spectra (Figure 1). We would expect that residual tropospheric and ionospheric effects are negligible in our reprocessed GPS. What is perhaps surprising is that there appears to be no significant GPS J_2 semi-annual residual. The GPS and SLR technique specific signals have no effect on the longer term J_2 long-term signal which we examine below.

[12] Large K2 (3.73 years) and S2 (0.44 years) tidal aliasing signals have been identified in GRACE J_2 series from CSR (Center for Space Research) and GFZ (GeoForschungsZentrum) RL04 [*Chen and Wilson*, 2010; *Chen et al.*, 2009]. A number of authors replace GRACE J_2 coefficients with those from SLR, or estimate 3.73 and 0.44 year terms. We estimate 3.73 and 0.44 year terms of 2.28×10^{-10} and 2.4×10^{-10} from CSR J_2 series treated identically to those used here. S2 tidal aliasing is not observed in the DMT1 GRACE J_2 amplitude spectra (Figure 1) and K2 aliasing is considerably reduced. The load model has significant amplitude at 3.99 years, particularly in land hydrology (Figure 1). Given the short length of the GRACE series, we cannot also remove a K2 aliasing term from GRACE in addition to a 3.99 year term. The DMT1 GRACE series are however affected by K2 tidal aliasing, after subtraction of the load model a prominent 0.72×10^{-10} peak at 3.73 years remains in the DMT1 series.

3.4. Long-Term Signal

[13] To isolate signals longer than 1 year, we smooth the coefficients with a 52-week running average (12 monthly for GRACE). The results are plotted in Figure 2 (middle). The 1998 anomaly is clearly visible in the GPS, SLR and load model J_2 series. Also plotted in Figure 2 (bottom) are smoothed GPS minus load model, SLR minus load model and GRACE minus load model J_2 series. We make the following observations regarding the long-term signal:

[14] 1. The GPS and SLR long-term J_2 signals are better correlated with each other (0.82) than with the load model. GPS is better correlated (0.73) with the load model than SLR (0.56).

[15] 2. GPS and SLR J_2 both deviate from the load model during the upward leg of the 1998 anomaly (1998–2000) but

the GPS derived J_2 can be up to 0.5×10^{-10} closer to the load model than SLR. The RMS of the GPS minus load model and SLR minus load model series for 1998–2000 are 0.52×10^{-10} and 0.96×10^{-10} respectively.

[16] 3. During the return leg of the 1998 anomaly (2000–2002), GPS and SLR are both close to the load model. The RMS of the GPS minus load model and SLR minus load model J_2 for 2000–2002 are 0.17×10^{-10} and 0.42×10^{-10} respectively.

[17] 4. The 1998 anomaly is evident in the load model J_2. Between mid 1997 and 2000, there is a trough in the load model and GPS J_2. This trough is not observed in the SLR J_2. Subtraction of the load model removes the 1998 anomaly from the GPS J_2 series, but does not completely remove it from the SLR J_2 series.

[18] 5. GPS and SLR derived J_2 agree best in the period 2001–2005.

[19] 6. From 2005 there are significant departures in size and overall pattern of GPS, SLR and GRACE J_2 compared to the load model and each other.

4. Long-Term Signal: Discussion

[20] A combination of land hydrology, ocean and atmosphere components along with an accelerating melting of sub-polar mountain glaciers has been used to explain the 1998 anomaly [*Dickey et al.*, 2002]. Our hydrology has larger amplitude than that of *Dickey et al.* [2002] thus we do not need to consider additional mountain glacial melt to explain the 1998 anomaly as observed by GPS. In Figure 2 (top), the smoothed load model series is plotted alongside the contributing components. It is apparent that the presence of a 1998 anomaly in the load model is due to a superposition of peaks. Crucial to this superposition is the succession of a strong negative (-1.0×10^{-10}, early 1998) and strong positive peak (0.87×10^{-10}, mid 2000) in the land hydrology. A succession of 0.60×10^{-10} peaks in the atmospheric component is also seen 1999–2001, along with a domed 0.37×10^{-10} peak in the oceanic component (1998–2002), centered on 2000.

[21] From 2005–2007 the GPS, SLR and GRACE long-term signals noticeably depart from the load model and each other. K2 aliasing likely causes enlarged amplitude of the GRACE signal in this period. The GPS secular correction is affected by the need to estimate co-seismic offsets for the Sumatra-Andaman (2005.0) and Nias earthquakes (2005.25). This likely explains the departure, since we find that a longer GPS time series returns the 2006.5–2008 outlying values close to the load model. Why the SLR departs from the load model from 2005–2006.5 is not understood.

[22] A number of authors suggest that the size of the 1998 anomaly could be an artifact of mismodelling 18.6-year tide anelastic terms. In particular, *Benjamin et al.* [2006] demonstrate that errors in the 18.6 year tide model could mask quasi-decadal and inter-annual cycles. In that study, the authors compute three versions of *Cox and Chao*'s [2002] J_2 series corrected using different 18.6 year tide models. Of particular interest is that the upward leg of the 1998 anomaly is more affected than the downward leg, and also the presence of the aforementioned trough seen in the load model and GPS J_2 (Figure 2). In fact, the trough is present in the best fitting tidal model corrected series of *Benjamin et al.* [2006] but not in their IERS 2003 tidal model corrected series. Since we use the IERS tidal model it seems plausible that mismodelling of the 18.6-year tide causes some of the observed departure of SLR J_2 from load model J_2 (Figure 2). Why the GPS would be less affected by anelastic mismodelling is a difficult question to answer. The GPS J_2 are generated by implicitly assuming a surface mass load nature during estimation. Thus, the propagation of anelastic modeling errors in the GPS tide model into GPS J_2 is not linear. We might speculate that while the GPS covers the same 13-year period as the SLR the individual site data spans are far from homogeneous and the shorter data spans used to estimate and remove tectonic rates from sites might dampen the affects of 18.6 year tidal mismodelling.

[23] The superposition of inter-annual terms with a decadal term was used by *Cheng and Tapley* [2004] to explain the 1998 anomaly. Our 13 year J_2 series are too short to reliably estimate a decadal term. However, we do observe a longer period signal (8–10 years) in both the GPS and SLR series after the load model is subtracted (Figure 2). The GPS and SLR amplitude spectra also indicate signal at 8.65 years (Figure 1), both before and after the load model is subtracted. We conclude that 8–10 year variation appears to exist in the GPS and SLR J_2, which is not explained by the load model. Since this quasi-decadal variation is larger than observed in the load model and other signals at this period are not expected, we follow *Cheng and Tapley* [2004] in calling it "unexplained".

5. Conclusions

[24] Spectral analysis of the J_2 time series from GPS, SLR, GRACE and load model has yielded strong similarities in amplitude between GPS and SLR for the annual cycle over the same 13 year time span. The load model (GLDAS continental hydrology; NCEP reanalysis atmospheric pressure; ECCO ocean mass) effectively removes the annual signal in the GPS, SLR and GRACE. The SLR semi-annual signal is larger than that in GPS and remains significant after removal of the load model. A significant semi-annual term is not seen in the GRACE series. Technique specific terms exist at 1.24 years for GPS and 0.3 years for SLR. The GRACE inter annual peak at 3.73 years is likely enlarged by K2 tidal aliasing but we do not see the S2 tidal aliasing seen in other GRACE series.

[25] The long-term GPS and SLR signal exhibit an overall pattern and amplitude that is consistent with the load model but the GPS and SLR long-term signals are better correlated with each other (0.82) than with the load model (0.73 & 0.56). The long-term signal of GPS and SLR both deviate from the load model during 1998–2000 but are closer during 2000–2002. Mismodelling of the anelastic response to 18.6-year tide may cause some of the differences between the SLR and load J_2 time series. Again we emphasize that a trough in 1998 is present in the best fitting tidal model corrected series of *Benjamin et al.* [2006] but not in the IERS 2003 tidal model corrected series. Since we use the IERS 2003 tidal model for SLR (and GPS) we attribute some of the observed difference to this cause. It is, however, not clear why the GPS would be less affected by anelastic mismodelling.

[26] Using the GLDAS continental hydrology, we find that we do not need to consider additional mountain glacial melt to explain the 1998 anomaly as observed by GPS. The

GPS minus load model series shows a negative trend from mid 1996–2002, which would contradict the hypothesis that only acceleration of mountain glacial melt remains in the J_2 series. This study has shown that GPS is closer to the load model than SLR to the extent that subtraction of the load model removes the 1998 anomaly from the GPS J_2 series but not entirely from the SLR J_2 series. This might be used as evidence that the SLR anomaly may not be entirely due to mass re-distribution as was originally presumed.

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