Reconciling Estimates of Annual Geocenter Motion from Space Geodesy

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Abstract. *By construction, the origin of the reference frame is coincident with the mean Earth center of mass, averaged over the time span of the satellite laser ranging (SLR) observations used in the reference frame solution. At shorter time scales, tidal and non-tidal mass variations result in an offset between the origin and geocenter, called geocenter motion. Currently, there is no model for the annual variation. This annual motion reflects the largest-scale mass redistribution in the Earth system, so it is essential to understand it for a complete description of the total mass transport. Failing to model it can also cause false signals in geodetic products such as sea height observations from satellite altimeters. However, inconsistencies in the estimates of annual geocenter motion have prevented the adoption of a consensus model. In this paper, it is shown that the various estimates can be reconciled, and that models for the annual geocenter motion can be recommended, depending on the application.*

Introduction

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 et al. (2008) (referred to as SWC) combine the GRACE monthly estimates with a numerical ocean model to obtain the degree-1 variations. The Center for Space Research (CSR) also 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 amplitude of the annual variation in Y is reasonably consistent with SLR, but the amplitudes for X and Z are significantly smaller than seen from SLR, with a significant phase offset for Z as well. The difference in Z (about 3 mm) would represent a difference in the estimated seasonal mass distribution of over 200 GT in the Antarctica mass change estimates (Wu and Heflin, 2014).

The lack of an annual geocenter motion model also affects precision orbit determination, which is crucial for the application of satellite altimetry to monitor the sea surface changes. Satellite orbits that depend strongly on SLR tend to be tightly bound to the crust (through the ground-based tracking station coordinates) rather than following the true geocenter. Other tracking techniques, particularly GNSS, are less tightly bound to the crust and appear to be somewhat better centered. This leads to clear a seasonal signal in the orbits when compared to each other. Figure 1a illustrates this for the Jason-2 altimeter satellite, where an orbit based on SLR and DORIS is compared to an orbit based on GPS. The strong annual variation in Z component of the orbit difference is close in phase with the estimated geocenter motion. When the annual geocenter motion is modeled, the orbit difference is reduced by about half. The consequence of the orbit difference in terms of mean sea level is illustrated in Figure 1b. The application of a conventional geocenter motion model would make the altimeter results more consistent between different orbit determination strategies.

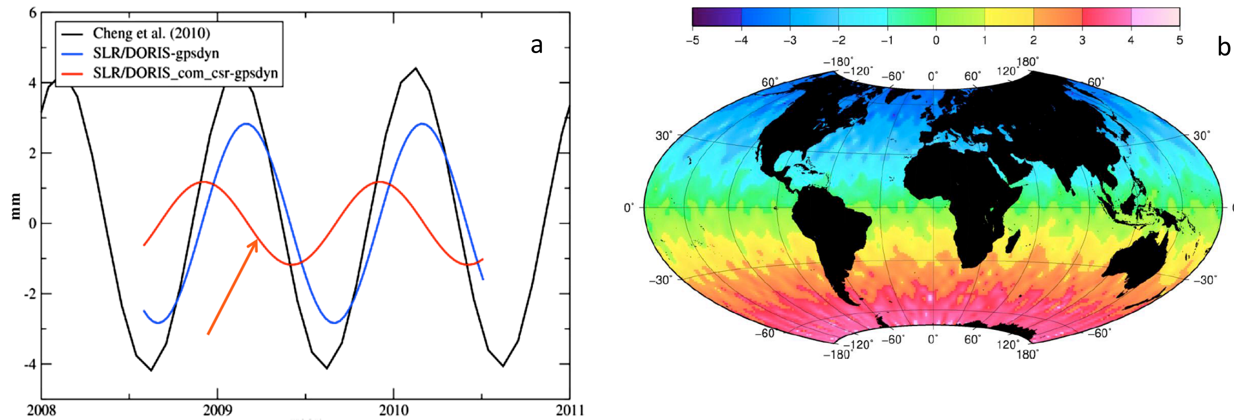

Figure 1. (a) Jason-2 orbit comparisons between GPS-based and SLR-DORIS orbits with and without modeling the annual geocenter motion. (b) Mean sea level signal (in mm) resulting from a geocenter motion model for Jason-2 cycle 58. (from Melachroinos et al., 2013)

Geocenter variations from GPS-global inversion and SLR

A degree-1 mass load on the Earth's crust has an observable impact on the crust-based tracking station positions; the visible nature of the impact is dependent on the reference frame one is using (Blewitt, 2003). From a crust-fixed reference frame, there is a deformation in the network where some stations move farther apart while others move closer to each other. From a frame fixed to the center of mass (solid earth, ocean, atmosphere), there is an observable translation.

The deformation signal is exploited by a global inversion approach using the global distribution of GPS stations with are sensitive to mm-level relative motions. In this approach, the signal of interest is the deformation from just the degree-1 deformation, so additional information is introduced to remove the higher degree (degree > 1) mass load signals. Recent analyses have accomplished this with the higher degree mass estimates from GRACE (over land) mixed with ocean bottom pressure (OBP) from an ocean model (e.g., Jansen et al., 2009; Rietbroek et al., 2012; Wu et al., 2006, 2010; Wu and Heflin, 2014). Figure 2a illustrates one of these solutions, and Table 1 provides some estimates from selected global inversion solutions. Note that the annual variation is quite regular and well-characterized by a simple annual sinusoid.

The translation signal is better observed with SLR, with its strong tie between the target satellite (which is orbiting the Earth's center of mass) and the crust. The seasonal variation in the geocenter has been a routine product of the various reference frame solutions, where the geocenter information is obtained exclusively from the SLR time series in a 'network shift' approach (e.g., Altamimi et al., 2011, 2016). Independent analyses have used a 'dynamic approach' where the network is held fixed but the translation is estimated simultaneously as part of the precise orbit determination procedure (e.g., Cheng et al., 2013; Ries, 2013). Figure 2b illustrates an updated time series from this study using the recently released ITRF2014 reference frame for SLR. These are 60-day estimates, to provide a cleaner time series, whereas the global inversion results are 30-day estimates. Table 2 provides some estimates from selected SLR solutions. Note the very good internal consistency in spite of the different processing strategies (network shift and dynamical approaches).

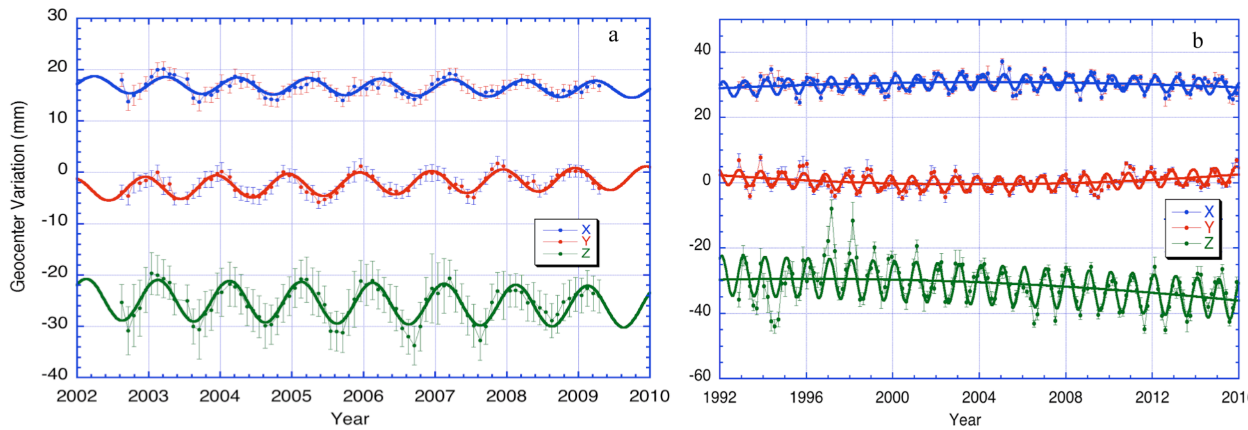

Figure 2. Geocenter time series from (a) GPS/GRACE/OBP global inversion (Wu et al., 2010), and (b) from SLR (this study). X and Z have been offset by + and -30 mm, respectively.

GPS Global Inversion	X (amp)	X (phase)	Y (amp)	Y (phase)	Z (amp)	Z (phase)	Reference (comments)
GPS loading + GRACE + OBP	1.8	46	2.5	329	3.9	28	Wu et al., 2006
GPS loading + GRACE	2.0	21	2.6	334	3.6	24	Jansen et al., 2009
GPS loading + GRACE + OBP	2.0	62	3.5	322	3.1	19	Rietbroeck et al., 2011 (updated June 2011)
GPS loading + GRACE + OBP	1.8	49	2.7	329	4.2	31	Wu et al., 2010
GPS loading + GRACE + OBP	1.9	25	3.3	330	3.7	21	Wu & Heflin, 2014
mean	1.9	41	2.9	329	3.7	25	
standard deviation	0.1	17	0.4	4	0.4	5	

Table 1. Annual geocenter motion estimates from the GPS/GRACE/OBP global inversion.

SLR results	X (amp)	X (phase)	Y (amp)	Y (phase)	Z (amp)	Z (phase)	Reference (comments)
SLR (ILRS)	2.6	40	3.1	315	5.5	22	Altamimi et al., 2011 (ILRS contribution to ITRF2008)
SLR (5 satellites)	2.7	40	2.8	323	5.2	30	Cheng et al., 2013 (weekly estimates;1993-2010)
SLR (ILRS)	2.6	46	2.9	320	5.7	28	Altamimi et al., 2016 (ILRS contribution to ITRF2014)
SLR (L1/L2)	2.8	47	2.5	322	5.8	31	Ries, 2016 (60-day estimates; 1993-2016)
SLR (L1/L2)	2.4	55	2.5	321	6.1	31	Ries, 2016 (60-day estimates; 1993-2016) ITRF2014
mean	2.6	46	2.8	320	5.7	28	
standard deviation	0.1	6	0.3	3	0.3	4	

Table 2. Annual geocenter motion estimates from SLR.

CF-CM vs CN-CM

The global inversion approach is often described as inferring the motion of the center of figure of the Earth relative to the center of mass (CF-CM) from the load deformation signal, while the SLR approach is instead observing the translation of the SLR network relative to the center of mass (CN-CM). The distinction between the center of mass of the solid earth (CE-CM) and the center of figure (CF-CM) is only a few percent, and no further distinction is made here. Ideally, in the absence of any higher degree loading effects and robust network distribution, these would represent the same geocenter motion, but it is clear when comparing the mean values in Table 1 with those in Table 2, there is a significant discrepancy between the two approaches for X and Z. Given the internal consistency for the two approaches, this discrepancy appears to be well outside reasonable uncertainty estimates, suggesting a systematic effect that is biasing one or both.

An ongoing concern has been the effect of the higher degree loading on the estimates of geocenter motion at the annual frequency from the relatively sparse SLR network, often denoted as the 'network effect' (e.g., Collilieux et al., 2009; Collilieux and Altamimi, 2009; Sośnica et al., 2013). One approach would be to apply a model for non-tidal atmosphere loading (NTAL), but the degree-1 component would need to be removed. Otherwise, a part of the geocenter motion signal of interest would be modeled away. The same thing would have to be done for forward modeling the hydrological loading. Another approach would be to employ the GRACE/OBP results in the same manner as the global inversion, but this would limit the geocenter estimates to only those months where a GRACE solution is available.

Given the above limitations, a new approach is tested to see if the data itself can provide a solution. Given that the local site loading is dominated by vertical motion and that the range bias is highly correlated with the vertical, the estimation of a bias for each site (every 30 or 60 days) should accommodate the local site motion (as well as any actual biases)[1]. To avoid absorbing the desired geocenter signal, a relatively tight apriori constraint is applied to the bias. Applying a relatively tight apriori (~2.5-3.0 times the aposteriori sigma or ~5 mm for the 60-day solutions) allows the common-mode signal from geocenter to go into the geocenter parameters (where there is no constraint) while the local motion that is not common-mode has a place to go. The constraint is not tight enough to prevent the bias from accommodating the spurious local signal, but it applies enough 'pressure' to keep out the geocenter signal of interest. Spectral analysis of the estimated biases shows a clear peak a the annual frequency, which is unlikely to be an actual range bias variation but rather shows that the annual local loading is being accommodated.

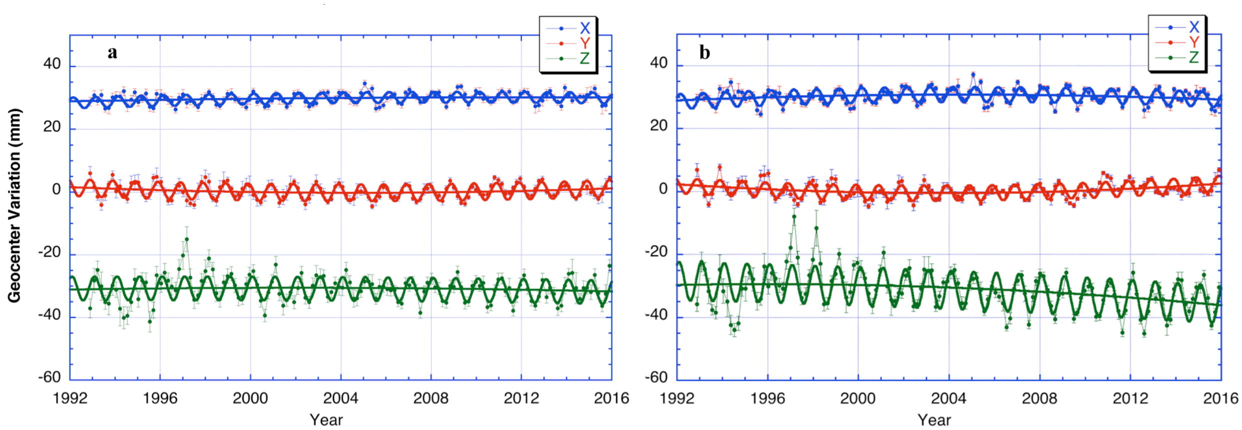

Figure 3. Geocenter time series from SLR (a) with and (b) without the addition of the constrained estimation of range biases. X and Z have been offset by + and -30 mm, respectively.

[1] Due to a software issue, the station heights could not be estimated simultaneously with geocenter motion, so the bias was used as a proxy because of the high correlation. However, the issue has been resolved and the results are nearly identical when the heights are estimated rather than biases. Any actual range biases will also be absorbed by the heights due to the high correlation.

As seen in Table 3, this strategy appears to resolve the discrepancy between the two approaches. The amplitudes for X and Z from SLR are now in close alignment with those from the global inversion; Y is unchanged and its agreement remains intact. If the method was merely reducing the amplitudes, then Y should have been similarly affected, but instead the amplitude was reduced by only 0.1 mm. Given that the two methods are fundamentally different, using different data and based on different signals, the level of agreement suggest that considerable confidence can be placed in a 'Climatologial model' for the annual geocenter variation (CF-CM). This confidence is further enhanced when compared to the average of 8 geophysical models that were selected for their consistency with the geodetic estimates. Furthermore, when the contribution from the atmosphere and ocean (GRACE AOD1B) is restored to the results from SWC, there is remarkable agreement now for X and Y. The amplitude for Z is still considerably underpredicted in SWC; this remains an open question; perhaps the use of an ocean model rather than GRACE over the ocean or perhaps some other limitation.

Comparison	X (amp)	X (phase)	Y (amp)	Y (phase)	Z (amp)	Z (phase)	
SLR (L1/L2)	1.9	50	2.8	321	3.9	28	This study (mean of 4 SLR solutions using ITRF2005 and 2014)
GPS loading + GRACE + OBP	1.9	41	2.9	329	3.7	25	Mean of GPS global inversion results (from Table 1)
New 'Climatological model'	1.9	45	2.9	325	3.8	26	Average of SLR and GPS results
Geophysical models	2.3	31	2.2	333	3.1	33	Mean of 8 geophysical models
GRACE+Ocean Model	2.2	43	3.0	333	2.7	42	SCW, 2008 (updated 2012, AOD restored)
AOD	1.3	9	1.6	350	0.9	364	AOD1b (RL05, 2002-2014) (GAC)
Climatological model wo AOD	1.3	86	1.5	293	3.3	34	Degree-1 with AOD removed (GSM)
GRACE+Ocean Model	1.3	92	1.4	282	1.8	87	SCW, 2008 (updated 2012, AOD not restored)

Table 3. Summary of annual geocenter motion estimates from various approaches.

Conclusions

The nominal SLR estimates of geocenter motion are consistent with the IERS conventions concept of a correction to center the ITRF (in particular, the SLR stations) on the mass center of the Earth. Applying this correction improves the centering of SLR-based orbits. This "CN-CM" correction is likely applicable to DORIS as well, as the same sort of local site motion will affect SLR/DORIS orbits This correction is not appropriate if NTAL is being forward-modeled, but rather, the "CF-CM" model should be more appropriate (however, it should be noted that the degree-1 component should not be included in the NTAL in this case, since a part of the geocenter motion is due to the degree-1 part of the atmosphere mass variations). By providing an accommodation for the local (spurious) site motion (as well as actual bias variations), the estimates of annual geocenter motion from SLR finally become aligned with those from GPS/GRACE/OBP global inversion. After removing the contribution from the atmosphere/ocean (AOD1B), the SLR/GPS results agree well with Swenson et al. (2008), except for the Z component; the GRACE/OBP inversion appears to miss some of the signal and has a significant phase offset.

Acknowledgements

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