# Can we Measure Geocenter Motion Accurately?

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## 1. Introduction

It is ten years since the IERS Campaign to investigate motion of the geocenter. One conclusion from that campaign was "It appears that even if Space Geodesy geocenter estimates are sensitive to seasonal variations, the determinations are not yet accurate and reliable enough to adopt an empirical model that would represent a real signal" [*Boucher and Sillard 1999*]. So where are we 10 years later?

Geocenter motion is a consequence of Earth deformation, it is the translation vector that represents the average deformation of the Earth seen by satelites. Other than surface mass loading we know of no other cause of seasonal geocenter motion. Knowledge of geocenter motion is important for two reasons, 1) the biggest contributor to non-secular geocenter motion is likely the re-distribution of the surface mass load [*Dong et al., 1997*], thus knowledge of geocenter motion can help us model surface mass processes and 2) until we can measure or model geocenter motion accurately the Terrestrial Reference Frame will have an instability in the origin caused by geocenter motion.

## 2. Definitions + Methodology

Here we define geocenter motion to be the vector displacement $\Delta r_{CF-CM}$ of the geometrical center of figure of the Earth (CF) from the Center of Mass of the entire Earth system (solid Earth+oceans+atmosphere). Note this definition is not unique, its opposite in sign is as common in the literature. There are essentially two styles of method to estimate geocenter motion from satellite techniques:

**Network shift (GPS/SLR/DORIS):** Satellite techniques give us site displacements $\Delta s_{CM}$ in the CM frame, the average of these site displacements gives an estimate of geocenter motion. Since site displacements due to loading are not a pure translation (see box 3.) this method can suffer from aliasing due to a poorly distributed network. This method is favoured for SLR since the orbit errors are smaller than GPS and the network distribution is too poor for inversion methods

**Inversion Methods (GPS):** The site displacements $\Delta s_{CM}$ in the CM frame are not a pure translation (see box 3.), the actual displacements due to loading can be modelled in the CF or CM frame using elastic loading theory. A dense global site coverage is required for inversion, limiting this method to GPS. Even with GPS the problem is ill posed and requires regularisation or physically motivated constraints. Inversion relies more heavily on inter-site deformation observed by GPS which is generally thought to be inherently less sensitive to translational orbit modelling errors.

## 3. Network Shift Versus Inversion methods

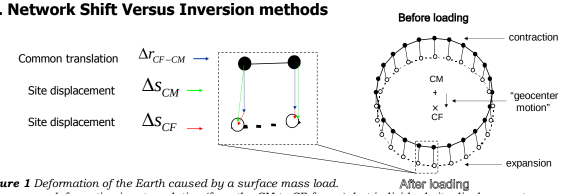


***Figure 1*** *Deformation of the Earth caused by a surface mass load. The average deformation is a translation (from the CM to CF frame), but individual site displacements vary. Here we show only degree-1 deformation, higher degrees give further site displacements in the CF frame.*

## 4. Suitability of Annual+Semi-Annual model

To gauge accuracy we wish to compare estimates from different techniques and to different loading models. Comparison between different published estimates is usually via annual or annual+semi annual fits.

Is the annual+semi annual a reliable model for this comparison? Different published estimates are estimated from different windows of data (3-13 yrs in Fig 3) starting at different times.

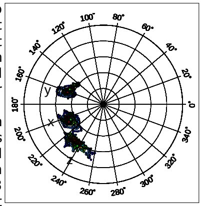


***Figure 2*** *Estimated annual signal amplitude and phase from annual+Semi annual fits to Clarke et al., [2007] loading model (1995-2005) using a sliding window. Sliding window lengths are 1.5, 2.0, ... 4.5, 5.0 (blue through red). Green triangles are values estimated from full 10 year period.* ***Amplitude axis gridlines are at 1mm.*** *The phase convention in all plots is:*

$$A\cos[2\pi(t-t_0)-\Phi]$$

Our results suggest that we should expect significant variation due to estimation over different data windows, even with 5 years of data we can expect variation in annual amplitude up to 2mm and 10 degrees in phase on top of any model differences or technique/method specific measurement errors.

## 5. Comparison of Published Geocenter Motion Annual Signal

Figure 3 compares all published annual amplitudes and phases found by the authors (see separate table for references). We note the following:

We know of a likely systematic error source in almost every result plotted in Figure 3. See Clarke et al., [2005]; Lavallee et al., [2006]; Tregoning & van Dam., [2005]; Wu et al., [2002]; Willis, [2006], box 4 and box 7 for details, not all these errors are fixable in future estimations.

Values from common techniques are not independent, neither are the load model values, they too have common parts. There is some overlap between some GRACE, GPS inversion and loading models (e.g. ECCO)

There are few published results for GPS via the Network shift method, 3 of the 4 available are estimated from < 3 yrs of data.

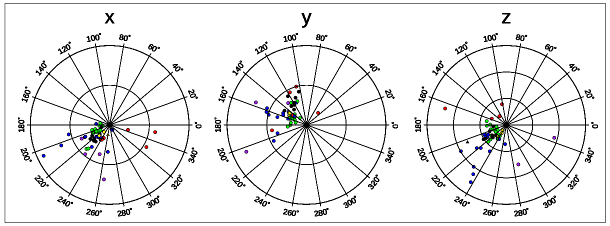


***Figure 3*** *Comparison of Published Annual signal amplitude and phase.* ***Amplitude axis gridlines are at 5mm****. Black: SLR, Red: DORIS, Purple: GPS, Blue: GPS-inversion, Yellow: GRACE, Green: Load models. Results from this work (see box 8) are plotted as triangles. One DORIS result [Altamimi et al., 2007 see supplementary table] is omitted as it is off the scale. Sign and phase convention conversions were applied (see geocenter motion definition box 2 and phase convention box 4.)*

## 6. Seasonal Geocenter Motion from GRACE

Preliminary geocenter motion estimates from GPS tracking of GRACE do exist [Konig et al. 2005, Zhu et al., 2004] but full results have yet to be published.

An alternative has been developed by Swenson & Wahr [2008] by combining GRACE and ocean model output. Here we try a similarly motivated approach. We fit the GRACE degree 2-30 total load with degree 2-10 modified basis functions [Clarke et al., 2007] via least squares. This basis parameterises a degree 0-30 load on land plus it's corresponding 0-30 degree equipotential ocean. Mass conservation is enforced. We use the sum of the CSR Release 4 GSM and GAC products after removing a secular term. These preliminary results are plotted alongside GPS and SLR in Figures 6 and 7 box 8.

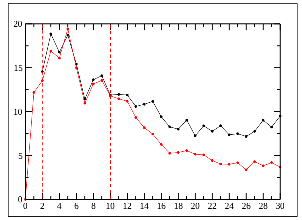


***Figure 4*** *Degree amplitudes (mm) of annual+semi annual signal in the CSR load (red) and fitted load (black). The region between vertical dashed lines corresponds to the part of the land load constrained by the data, outside of this region the combination of data and physical constraints predicts the load.*

## 7. Higher Order Ionosphere effects on GPS and GPS-inversion estimates

Neglecting higher order ionospheric effects in the GPS processing will affect geocenter motion estimated by the Network shift approach [Fritsche et al., 2005] and may affect an inversion approach. We difference geocenter estimates from corrected and uncorrected GPS solutions for both approaches. The largest effects (z) are 1.3mm RMS and 9.8 mm RMS for the inversion and Network shift approaches respectively. The effect on the estimated annual amplitude and phase is < 0.01 mm and < 5 degrees for the inversion approach and < 0.3 mm and < 8 degrees for the Network shift approach.

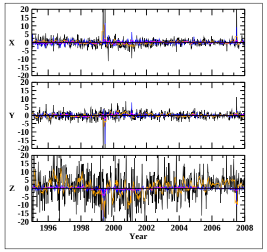


***Figure 5****. Difference (mm) between geocenter motion estimated from higher order ionosphere corrected and uncorrected time series. Black: Network shift with 8 week running average (orange), Blue: Inversion approach (see box 8) and 8 week running average (magenta)*

## 8. Reprocessed GPS-inversion and SLR Geocenter Motion Estimates

We estimate Geocenter motion from 13 years of weekly reprocessed GPS and SLR solutions 1995-2008.

**GPS**: We use an Inversion approach for GPS displacements in the CM frame (see box 2) with mass conserving, land/ocean partitioned basis functions [Clarke et al., 2007]. We use a higher-order ionosphere model (see box 7) and absolute antenna phase center models in the GAMIT reprocessing.

**SLR**: Network shift approach from loosely constrained weekly solutions from LAGEOS 1 & 2.

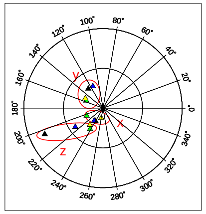


***Figure 6*** *Comparison of estimated geocenter motion annual signal amplitude and phase.* ***Amplitude axis gridlines are at 5mm****. Black: SLR, Blue: NCL GAMIT GPS-inversion, Yellow: GRACE, Green: Load models, Orange: NCL combination of IGS Reprocessing results.*

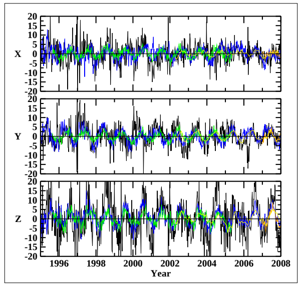


***Figure 7*** *Comparison of estimated geocenter motion time series (mm). Black: SLR, Blue: NCL GAMIT GPS-inversion, Yellow: GRACE, Green: Load models, Orange: NCL combination of IGS Reprocessing results. GRACE are monthly, all others weekly.*

## 9. Conclusions

Although discouraging, Figure 3, box 5 is an advance since the IERS campaign

When comparing annual geocenter motion, consistent data windows should be used wherever possible (box 4.)

When publishing annual amplitude and phase, it could be misleading to compare to only one or two other published estimates without strong evidence of the superiority of that measurement over others (box 5.)

Our latest results from GPS, SLR, GRACE and loading models show good agreement (box 8.)

The effect of higher order ionospheric effects on estimate annual geocenter motion is significant for the Network shift approach but insignificant for a CM frame inversion approach (box 7.)

Preliminary results of geocenter motion estimated from GRACE via land/ocean partitioning are encouraging (box 6 &8.)

With respect to the question in the title, we tentatively suggest that it is possible to estimate geocenter motion with an accuracy of 2-3 mm and 20 degrees in phase. This is however the same size as the predicted signal.

## References

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