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ORIGINAL ARTICLE

Observed geocenter motion from precise orbit determination of GRACE satellites using GPS tracking and accelerometer data

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Abstract

We present a method to estimate geocenter motion through single low-earth orbiter (LEO) precise orbit determination (POD) using global positioning system (GPS) tracking data and accelerometer data from the GRACE satellites. We fix the values of the GPS ephemerides and time-varying clock offsets to precise estimates from the definitive constellation product produced by the Jet Propulsion Laboratory. As part of the POD process of the LEOs, we estimate a translation of the reference coordinate system realized by the GPS orbit and clock product. Doing so accounts for the inconsistency between the Earth's center of mass coordinate system used for the orbit integration of the LEOs, and the terrestrial reference frame produced by the GPS orbit and clock product. The resulting translation parameters estimated separately from the GRACE-A and GRACE-B satellites show very similar variations from day to day. They represent the geocenter motion, as realized from the difference between the origin of the terrestrial reference frame represented by the GPS orbit and clock product and the Earth's instantaneous center of mass defined by the GRACE satellite dynamical orbital motion. Comparisons with geocenter motion observations from other techniques show that our daily estimates of geocenter motion agree well, when smoothed, in both the amplitude and phase of the annual signal. This validates both the high sensitivity of the GRACE GPS measurement type to geocenter motion and the high precision of the GRACE force model enabled by accelerometer measurements, the two essential components for estimation of geocenter motion with this technique.

Keywords Geocenter · GRACE · GPS

1 Introduction

The measurements of non-gravitational accelerations by accelerometers onboard geodetic satellites such as GRACE (Tapley et al. 2004) enable high precision orbit modeling for the determination of the Earth's gravity field. These measurements are usually provided as tabulated functions of time and provide a more accurate representation of the effects of non-gravitational forces—such as atmospheric drag, solar radiation and Earth radiation pressures—than are provided by models. In theory, accurate measurements of these non-gravitational accelerations along the satellite trajectory together with a spatially dependent model of the geopotential allow the satellite ephemeris to be precisely integrated. Estimating only the initial state of the orbit ephemeris and a few calibration parameters for the accelerometer measurements of non-gravitational acceleration over the specified orbit solution arc enables a precise fit to the GPS tracking data with the integrated orbit ephemeris. In practice, however, the result of such dynamic precise orbit determination (POD) for the GRACE satellites has proven to have limitations (Kang et al. 2006; van Helleputte and Visser 2008). Additional empirical force model or stochastic accelerations are often needed to accommodate remaining force model errors, for example, to account for time-varying gravity due to the Earth's mass transport in the case where a static geopotential model is applied to the orbit integration. The reduced-dynamic orbit solutions provided on the GRACE project Level-1 products still use force models instead of accelerometer measurements and accommodate model errors by estimating empirical accelerations with particular stochastic properties (Bertiger et al. 2002). These orbit solutions have provided an enduring standard for orbit determination accuracy of the GRACE satellites and have been used for

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various purposes by the worldwide geoscience community (Kang et al. 2006; Chen et al. 2015; Calabia and Jin 2016).

Besides these regular reduced-dynamic POD, efforts have also been made by the GRACE team at the Jet Propulsion Laboratory (JPL) to investigate dynamic POD for the GRACE satellites using accelerometer measurements in place of traditional non-gravitational force models. One approach has been to estimate a time series of stochastic accelerations to account for the deviation of the time-varying gravity field from the static model. This approach significantly improves the fit to the GPS tracking data (i.e., lower post-fit residuals) as might be expected from the estimation of a larger number of parameters. Furthermore, with this approach, we observe improvement in the consistency between orbit solutions, as measured by differences between neighboring daily 30-h orbit arcs as well as the inter-satellite K-band ranging data residuals. However, the estimated stochastic accelerations show puzzling biases, as described by Kuang et al. (2014), even though overall accelerometer instrument biases have already been estimated in the GRACE Science Reference Frame (SRF). These biases embedded in the stochastic acceleration time series are primarily in the cross-track direction and are almost identical for the GRACE-A and GRACE-B satellites. After a large number of experiments, the biases in the stochastic acceleration time series were removed by translating the whole constellation of the GPS satellites by estimating a coordinate system translation common to all GPS orbit positions. This leads to further investigation into the issue of consistency between coordinate systems used in the POD process.

The equations of motion for a satellite orbit are integrated in an inertial coordinate system. The tracking of the satellite's motion, however, is usually carried out with instruments tied to or associated with the Earth's surface that rotates in inertial space. Various computations for measurement modeling are performed in the Earth-fixed system. Ideally, both systems have their origin coinciding with the Earth's instantaneous center of mass (CM). In such systems, the Earth's gravitational potential model has the simple form of a spherical harmonic function with degree-1 terms set to zero. The position of an object expressed in the earth-centered inertial (ECI) system and in the earth-centered earth-fixed (ECEF) system is linked through a series of coordinate rotations:

$$\boldsymbol{r_i} = \boldsymbol{PNUXYr_f} \tag{1}$$

where $\boldsymbol{r_i}$ is the position vector in the ECI system $\boldsymbol{r_f}$ is the position vector in the ECEF system. The terms $\boldsymbol{P}$, $\boldsymbol{N}$, $\boldsymbol{U}$, $\boldsymbol{X}$ and $\boldsymbol{Y}$ are the conventional rotational operations for precession, nutation, Earth rotation and polar motion, respectively, that define the orientation of the ECEF coordinate system in inertial space. In practice, however, the exact location of the CM is unknown, and the ECEF coordinate system is realized through a group of ground stations whose coordinates are assigned to place the origin of the system at the long-term CM (Dong et al. 2003; Altamimi et al. 2007, 2011). The origin of such ECEF realizations also represents the center of the ground network (CN) and is an approximation to the center of figure (CF) of the solid Earth (Wu et al. 2012). In fact, measuring the exact location of CM and aligning the ECEF origin to it has been a long-term and ongoing task of the international geodetic community. The International Terrestrial Reference Frame (ITRF) provides a conventional realization of the ECEF (Altamimi et al. 2011, 2016). Thus far, the commonly accepted measure of the CM location relative to the ITRF has been considered to be provided by the Satellite Laser Ranging (SLR) technique which measures the distance between a ground station and a satellite. This technique produces estimates of the CM location at monthly or weekly time resolutions (Watkins and Eanes 1997; Altamimi et al. 2011; Cheng et al. 2013; Sosnica et al. 2014). Based on the assumption that all of the Earth's mass redistribution occurs on the surface of the Earth, geophysicists have developed inversion methods to infer the geocenter motion using crustal load-deformation measurements and/or ocean bottom pressure measurements combined with gravity measurements (Wu et al. 2002; Blewitt 2003; Swenson et al. 2008; Rietbroek et al. 2009; Sun et al. 2016; Wu et al. 2017). The ground GPS tracking technique also measures the distance between a ground station and a GPS satellite but altered by unknown clock offsets and carrier phase biases. This complexity, or "collinearity" issue when these biases are estimated, weakens the sensitivity of the fundamental observations to the CM (Altamimi et al. 2011; Rebischung et al. 2013), though the abundance of GPS data helps to mitigate this effect. After decades of continually increasing data volume (Vigue et al. 1992; Lavallee et al. 2006; Haines et al. 2011; Haines et al. 2015) the CM solution from ground-based GPS has improved significantly, but the weakness is still noticeable, mainly along the Earth's spin (Z) axis. Errors in force models for the GPS satellites, especially for solar radiation pressure, potentially introduce errors with associated patterns such as the variation in the 351-day "draconitic" period (Haines et al. 2015). However, the use of GPS-based POD of LEOs overcomes the CM sensitivity weakness of ground GPS tracking. The geocenter location information embedded in the GPS-based tracking of LEOs has been recognized and explored in various ways (Kang et al. 2009; Tseng et al. 2017). The mission concept Geodetic Reference Antenna in Space (GRASP) was proposed by Bar-Sever et al. (2012) to exploit this enhanced sensitivity. Kuang et al. (2015) demonstrated through simulation the significant increase in sensitivity by combining GPS tracking of LEOs and ground stations. Haines et al. (2015) augmented the real ground GPS tracking network with GRACE GPS tracking data and verified that the 351-day draconitic signature in the estimated geocenter motion vanished. With the improved sensitivity to the CM achieved with GPS-based tracking of LEOs, the remaining challenge is to reduce the dynamic force model errors of the LEOs as much as possible so that they do not introduce their associated signatures into the geocenter estimates.

In this paper, we present a simplified method to estimate the CM location using GRACE GPS tracking data through single LEO POD without explicitly using ground GPS tracking data. We fix the GPS constellation orbit positions and clock biases to those generated by the JPL IGS analysis center in a fiducial-fixed reference frame (Dow et al. 2009). We demonstrate that the LEO orbit and ground network is effectively linked through the fiducial GPS orbit and clock product, especially when the single-receiver ambiguity resolution technique is applied, although no ground station data are directly used (Bertiger et al. 2010). We focus on improving the modeling of GRACE orbital dynamics through the appropriate use of accelerometer data. An overall shift in the origin of the frame defined by the GPS constellation orbit and clock product (i.e., the ITRF) is estimated to account for its offset with respect to the CM that is assumed for the dynamical GRACE satellite orbital motion. The resulting geocenter motion estimates are presented and compared with results from other techniques.

2 Method to determine the geocenter motion from LEO GPS tracking

In our study we use the JPL GPS satellite orbit and clock products that are provided in the IGS14 terrestrial reference frame (the IGS realization of the ITRF2014 reference frame from Altamimi et al. 2016), as realized by fixing the coordinates of a group of GPS ground stations while performing the POD of the GPS constellation. Following current convention, in the IGS14 frame the origin is designed to coincide with the Earth's CM over the long term (e.g., years to decades), but does not track its short-term motion (mainly annual) stemming from the seasonal redistribution of water mass on or near the Earth's surface.

In the LEO POD solution, the measurements are the distances between the GPS satellites and the LEO satellite, also altered by the unknown clock and carrier phase biases. By fixing the GPS satellite orbits and clocks to the fiducial product, the purely geometric LEO orbit position solution is effectively linked to the corresponding fiducial frame through the LEO GPS measurements. The single-receiver ambiguity resolution technique (Bertiger et al. 2010) further strengthens the connection between the LEO orbit solution and the frame of the GPS orbit and clock product.

Figure 1 testifies to the strength of this link through a comparison between two sets of kinematic orbit solutions

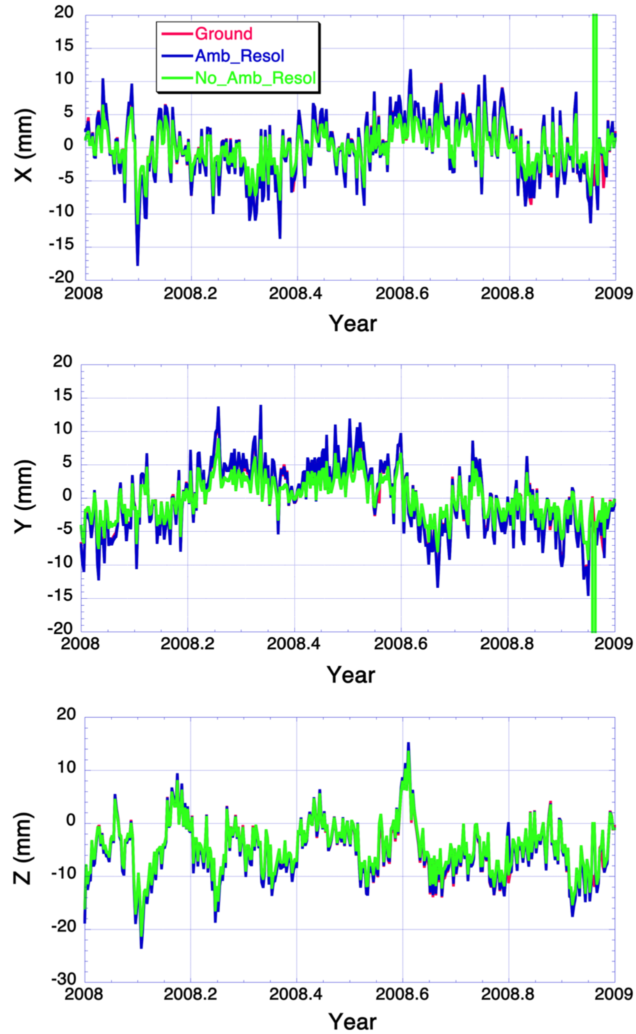

Fig. 1 Comparison of fiducial versus NNR frame transfer from ground network to LEO through GPS orbit and clock products using kinematic POD. The translation between IGS14 and NNR ground network station positions is shown in red. The translation between the LEO orbit positions using kinematic POD derived from fiducial- and NNR-based GPS orbit and clock products are shown in blue and green for the two cases with and without ambiguity resolution, respectively

for the GRACE-A satellite. Kinematic orbit solutions determine the position of the LEO based purely on the geometry of the receiver with respect to the transmitting GPS satellites, ignoring all force models and orbit integration. For the GPS orbit and clock products, we use two alternatives: the nominal (fiducial) product and a no-net-rotation (NNR) product, in which the ground network is free to translate (but not rotate) with respect to IGS14. The NNR implies that the ground network seeks to place its origin at the quasi-instantaneous origin of the GPS internal frame. The two frames (IGS14 via fiducial constraint and GPS internal via NNR constraint) differ by a translation that can be estimated from the two sets of ground network station positions. The two corresponding LEO orbit solutions also differ, by a translation that can

Table 1 Precision of fiducial versus NNR frame transfer through GPS products represented by the RMS difference between the translations in LEO orbit positions and ground network positions

LEO-network	RMS X (mm)	RMS Y (mm)	RMS Z (mm)
W/O Amb_Res	1.2	1.3	0.9
With Amb_Res	0.3	0.3	0.8

be estimated from the two sets of LEO orbit position coordinates. The two translations match each other, especially when resolving the integer ambiguities in the GPS phase measurements, to the submillimeter level in an RMS sense as shown in Table 1. This means the origin of the reference frame (as realized by the ground network) is effectively communicated to the LEO orbit via the GPS orbit and clock product, even though there is no ground station directly involved in the LEO orbit determination process.

When dynamic constraints are applied in the LEO POD process, imperfect force models may perturb the LEO orbit to differ from the measurements and cause the LEO orbit solution to be misrepresented in the reference frame, unless we properly account for the errors in the dynamic models. One of the imperfections in the dynamic models is the inconsistency between the origin of the reference frame and the actual center of mass of the Earth system. Like other conventional terrestrial reference frames, the origin of the IGS14 reference frame does not lie exactly at the instantaneous center of mass of the Earth system, due primarily to annual variations from the seasonal redistribution of water mass. To account for the fact that the reference frame does not represent the instantaneous CM, the transformation between the ECI coordinate system and the actually realized terrestrial reference frame can be expanded from Eq. (1) to include a geocenter offset, $\Delta \boldsymbol{r_g}$ that represents the location of the CM in the reference frame.

$$\boldsymbol{r_i} = \boldsymbol{PNUXY}(\boldsymbol{r_f} - \Delta \boldsymbol{r_g}) \tag{2}$$

This transformation between the coordinates expressed in a conventional ITRF and its corresponding expression in a conventional ECI coordinate system applies to any position vector. Correspondingly, the range from the LEO GPS measurement is:

$$\rho = |\boldsymbol{R} - \boldsymbol{r}| \tag{3}$$

where $\boldsymbol{R}$ is the receiver position vector and $\boldsymbol{r}$ the transmitter position vector, both in the ECI coordinate system, transformed using Eq. (2) whenever necessary. For LEO POD, $\boldsymbol{R}$ is integrated from the equations of motion in ECI, thus not transformed. On the other hand, $\boldsymbol{r} = (\boldsymbol{r_f} - \Delta \boldsymbol{r_g})$, where $\boldsymbol{r_f}$ originates with the GPS orbit and clock product, and the term $\Delta \boldsymbol{r_g}$ then accounts for the translation between the ECEF frame and the frame of the GPS orbit and clock product. For a reference frame realized by a ground station network, this definition of $\Delta \boldsymbol{r_g}$ is consistent with the conventional definition of the CM-CN vector where CN is the center of the ground network used to generate the GPS orbit and clock product. The variation of $\Delta \boldsymbol{r_g}$ in time then represents the geocenter motion in the given reference frame.

In this study, we perform daily dynamic POD of each of the GRACE satellites using the fiducial GPS orbit and clock product. We process 30-s GPS pseudo-range (PC) and carrier phase (LC) measurements to estimate a reference frame shift $\Delta \boldsymbol{r_g}$ using the observation Eq. (3) with frame transformation Eq. (2) for each LEO POD orbit solution arc to account for the possible offset between CM and the origin of IGS14 realization during that time. A nonzero estimate of $\Delta \boldsymbol{r_g}$ represents the inconsistency between the IGS14 and the CM-based ECEF coordinate systems for dynamic LEO POD and represents the estimated location of the quasi-instantaneous CM in the IGS14 frame. The other estimated parameters in our GRACE POD process include initial orbital position and velocity, constant accelerometer (ACC) bias, accelerometer bias rate and scale in each direction of the Science Reference Frame (SRF) for onboard instruments, and the coefficients of a 20×20 geopotential spherical harmonic function as a correction to the a priori static model. The estimation of the lower degree geopotential model improves the gravitational force model by accounting for the time-varying gravity. It also enhances the instrument calibration parameter estimation, because the accelerometer parameters should be linked only to non-gravitational accelerations. Stochastic accelerations in the directions of the accelerometer system are also estimated at each tracking data time, to accommodate errors of the accelerometer measurements and estimated dynamic model parameters. Table 2 shows the models and strategy used in this study.

To focus on the feasibility of our method for geocenter motion determination, we choose the 4-year time span from 2006 to 2009. During this period, the GPS and accelerometer measurements from both GRACE satellites are of high quality. At the end of year 2005, the GRACE satellites were swapped, and the pattern of the GPS antenna calibration changed. After that, the GRACE-A satellite was in trailing formation with GPS occultation tracking turned on. Starting in year 2010, the temperature control onboard the GRACE satellites was turned off, leading to systematic variations in the accelerometer measurements that are difficult to calibrate. We choose high-rate (30-s) GPS tracking instead of the usual 5-min samples (as used in GRACE Level-1 POD products), to provide better spatial coverage for the 20×20 gravity resolution. We use a specific GPS calibration for the POD antenna (Haines et al. 2004) on each spacecraft and each measurement type that was determined using 1 year of 30-s ionosphere-free GPS pseudo-range and carrier phase

Table 2 GRACE POD strategy used in this study

Model	Parameters	Estimation	Update time
Background gravity	GIF-48 180 × 180	No	No
Time-varying gravity	20 × 20	437 Coefficients	Daily (per arc)
Orbit initial state	Position and velocity	6 Constants	Daily (per arc)
ACC biases	Along SRF X, Y, Z	3 Constants	Daily (per arc)
ACC bias rates	Along SRF X, Y, Z	3 Constants	Daily (per arc)
ACC scale	Along SRF X, Y, Z	3 Constants	Daily (per arc)
CM location $\Delta \boldsymbol{r}_g$	Earth-fixed X, Y, Z	3 Constants	Daily (per arc)
Residual acceleration	Along SRF X, Y, Z	3 Stochastic, 1 nm/s^2	30-s
Receiver clock	Bias	1 White noise	30-s
30-s PC and LC data	LC bias	1 Constant	Each data pass

measurements, respectively. These satellite-dependent calibrations account for the effect of the interference between the GPS occultation and POD antennas on GRACE-A (mostly in pseudo-range measurements, Montenbruck and Kroes 2003) and the effect of antenna phase center offset and multipath interference on both satellites. These calibrations are derived from an iterative process that uses post-fit tracking data residuals.

3 Results

For the main purpose of determining the geocenter motion over the study period, we use non-overlapping 24-h orbit solutions so that independent geocenter locations are estimated day by day. For the purpose of assessing the effect of frame inconsistency and dynamic model error on orbit precision, however, we use overlapping 30-h orbit solutions over a short test period so that orbit overlap differences can be formed. To illustrate the impact of key elements of our solution strategy, we evaluated three different solution strategies using data from the January 2008: dynamic POD without estimation of the frameshift parameter, dynamic POD with estimation of the frameshift parameter, and dynamic POD with estimation of the frameshift parameter and stochastic acceleration parameters to account for errors in the accelerometer data.

Summarized in Table 3 are the average of the daily root mean square (RMS) of a few metrics over the month. For the dynamic POD with or without frameshift estimation, the differences for data fit residuals and orbit overlap differences are small. The only significant improvement by estimating geocenter location shows up as improved agreement between the resulting inter-satellite range and the withheld K-band range measurements. However, estimating stochastic accelerations to account for the errors in accelerometer data significantly improves all error metrics. The daily RMS of the estimated stochastic acceleration is consistently below 0.05 nm/s^2 in the X direction of the instrument frame (near along-track), although the constraint on the first order Gauss Markov process is set relatively loose (1 nm/s^2 steady-state sigma and 30 s correlation time) in the filter. For Y and Z directions (near cross-track and orbital radial directions), the daily RMS value is around 0.01 nm/s^2, which is close to the level of measurement noise of the GRACE accelerometer (Flury et al. 2008). We also did a test solution by tightening the constraint on the stochastic acceleration to 0.05, 0.01 and 0.01 nm/s^2 for X, Y and Z components, respectively. All results remain almost the same, with changes at the level of 1% only. Apparently, the adjustment of stochastic accelerations in each 30-s interval does not change the global parameters in any significant way. The time series of estimated accelerations do not show noticeable biases in any of the three directions.

Table 3 One month (Jan. 2008) average effect (RMS) of estimating frame shift and stochastic accelerations

Statistics	Without shift	With shift	Shift and stochastic acc
PC residual	40.00 cm	40.00 cm	31.64 cm
LC residual	5.18 mm	5.16 mm	3.95 mm
Orbit overlap in H	3.47 mm	3.58 mm	3.33 mm
Orbit overlap in C	3.44 mm	3.42 mm	3.22 mm
Orbit overlap in L	3.28 mm	3.28 mm	3.09 mm
KBR residuals	3.10 mm	2.69 mm	2.28 mm

PC, pseudo-range measurement; LC, carrier phase measurement; H, orbital height direction; C, cross-track direction; L, along-track direction; KBR, K-band range measurement that is not used in the POD solution

The estimated frame shifts from GRACE-A and GRACE-B show very similar variations from day to day (as shown in Fig. 2). Over the entire study period the variation of our estimated frame shift, combined from GRACE-A and GRACE-B, agrees on seasonal scales with both the monthly (Cheng et al. 2013) and weekly (Sosnica et al. 2014) solutions obtained by using SLR tracking to multiple geodetic satellites. It also agrees well with the monthly solution

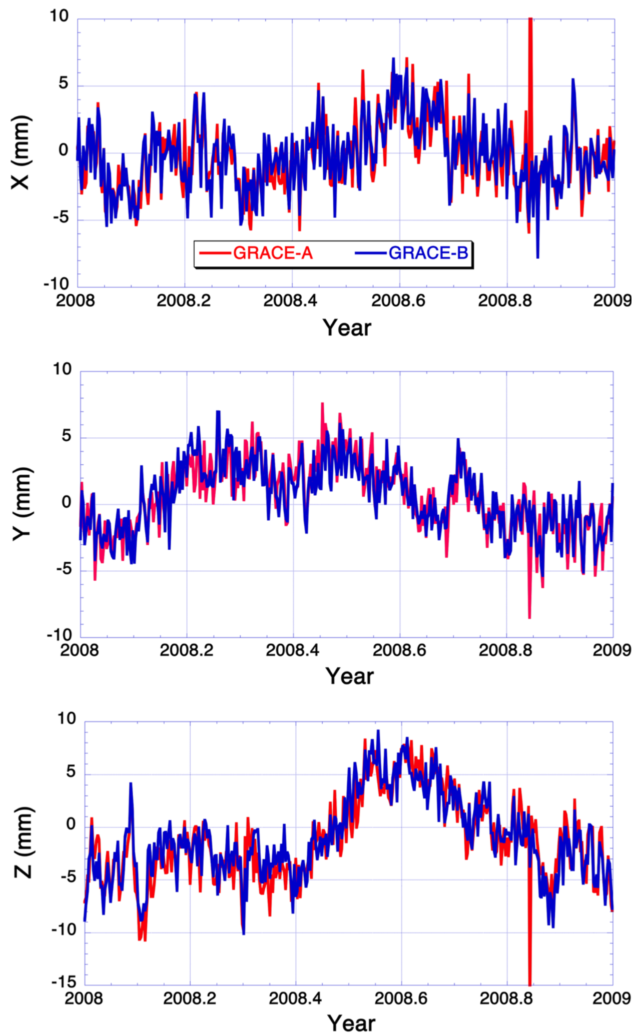

Fig. 2 Comparison of frame shifts estimated from GRACE-A and GRACE-B from POD solutions that also estimate stochastic accelerations

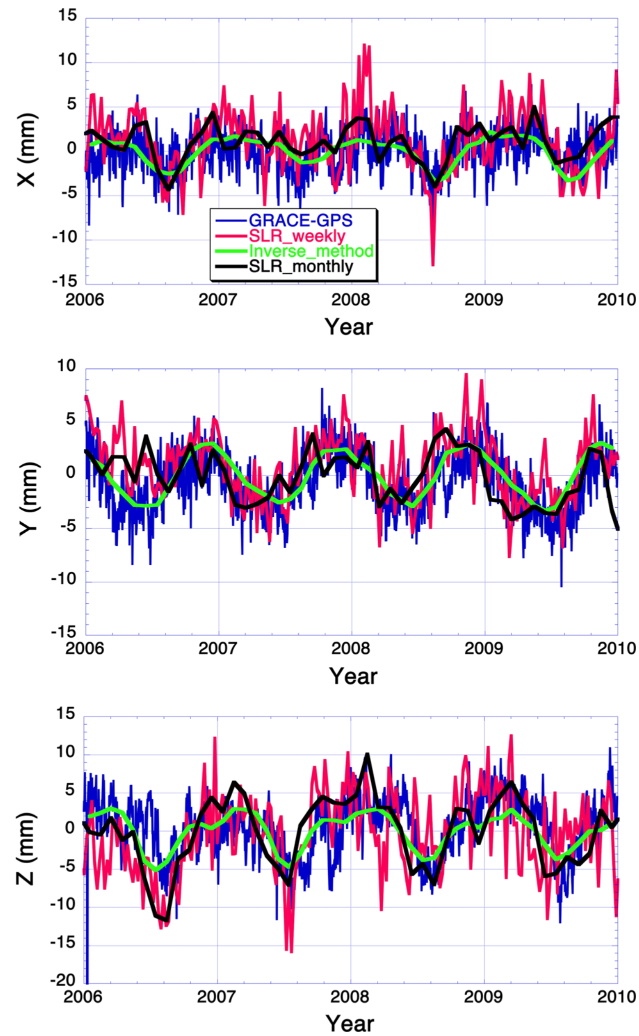

Fig. 3 Comparison of *X*, *Y* and *Z* components of geocenter estimates with other techniques

obtained through the unified inversion combining multiple data sources (Wu et al. 2017). The comparisons of each component of these solutions are shown in Fig. 3. The estimated amplitude and phase of annual term for each solution during this time period are listed in Table 4.

4 Discussion on the solution quality

Besides comparing our geocenter motion estimates with competing estimates from independent techniques, we can do more analysis to evaluate the quality of our estimated geocenter motion time series. One common concern about the method presented here is whether estimating geocenter together with gravity field would result in high correlation between those parameters, because geocenter offset is equivalent to degree one terms in the spherical harmonic expression of a gravity model. We checked over one month's solutions (Jan. 2008) and do not see any high correlation between the estimated geocenter parameters and gravity parameters that would corrupt the solution, even with the estimation of additional stochastic accelerations. Among these correlations on each day, only a few terms are greater than 0.2 during the month that was examined (Table 5). Clearly, estimating 20 × 20 gravity field and stochastic acceleration together does not constitute fatally heavy parameterization. A possible explanation is that in our solution the geocenter offset is treated as geometric parameter, which is not involved in orbit integration together with the gravity model.

In addition to the standard solution outlined in previous sections, we also made two other test solutions over a 1-year (2008) period. In one of the tests we do not estimate gravity parameters, and instead simply fix the gravity model to the static background model that is used in the standard solution. In the other test we do not estimate gravity parameters,

Table 4 Estimated annual amplitude and phase for each solution

Solution	X		Y		Z	
	Amp (mm)	Phase (day)	Amp (mm)	Phase (day)	Amp (mm)	Phase (day)
GRACE GPS	1.1	54	2.8	332	3.6	45
Monthly SLR	2.6	58	2.3	317	4.7	28
Weekly SLR	2.7	61	2.6	320	3.7	6
Inverse method	1.9	53	2.8	333	2.9	31

Table 5 Maximum correlation between geocenter and gravity parameters

Geocenter component	X	Y	Z
Gravity term	S (3, 2)	S (3, 2)	J (3)
Mean correlation	− 0.19	− 0.25	− 0.22
Max correlation	− 0.30	− 0.35	− 0.26

but fix the gravity field to the time-variant gravity model derived from monthly GRACE gravity products, hoping it will account for at least part of the natural time-varying gravity process. Figure 4 shows the stochastic acceleration time series estimated for all of the three treatments of the corresponding gravity models. It clearly demonstrates that adjusting gravity model parameters effectively reduces the error in the gravity model and other possible force model errors in the POD of GRACE satellites. With only 437 parameters for the 20 × 20 gravity model being estimated (much fewer than the 2880 stochastic acceleration updates for each component), the residual acceleration (green line) drops to near accelerometer data noise level. Without the gravity model adjustment, the perturbing acceleration (red line) is about 100 times larger. Even using a time-varying gravity model (blue line) does not reduce this error by much.

Figure 5 shows the comparison of formal error for the estimated geocenter parameters between the standard and test case solutions. Without gravity field estimation, the formal errors are the same regardless of the gravity model that is used. By simultaneously estimating a 20x20 gravity model, the formal error for the geocenter parameters increases by almost a factor of two. However, these formal errors are still at the submillimeter level, and there is no dramatic increase that would corrupt the solution. This is another indication of the suitability of estimating gravity field together with geocenter parameters. On the other hand, not estimating gravity field but estimating stochastic accelerations to absorb time-varying gravity model error has its own deficiency. Because the boundary between reduced-dynamic POD (which defines the CM) and the kinematic POD (which is independent of CM) is arbitrary, using different tuning strategies will result in different geocenter location estimates, a dilemma similar to the one faced by Tseng et al. (2017).

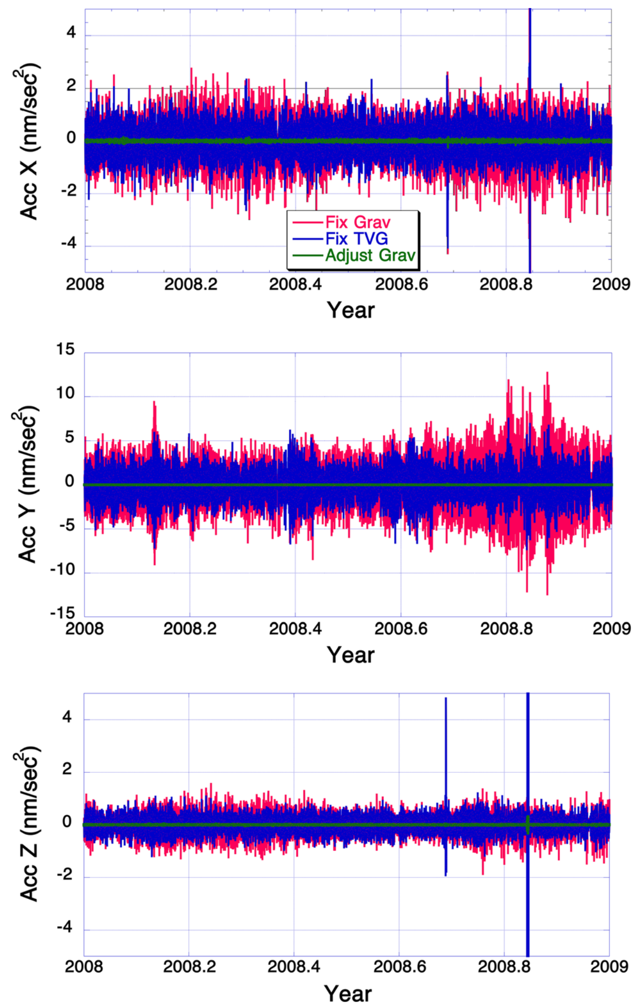

Fig. 4 Estimated stochastic accelerations in instrument coordinate system, red—fix static gravity model, blue—fix time-varying gravity model, green—estimate 20 × 20 gravity model

There is a signature of 2-times the GRACE draconitic frequency (~ 160-day period) in the formal error time series, regardless of whether the gravity field is estimated. That is the observability strength variation for each component due to the GRACE orbit plane motion in the inertial space. This signal is expected to subside when combining different LEO orbit planes.

While there are no geocenter estimates from other techniques available at comparable time resolution to justify or

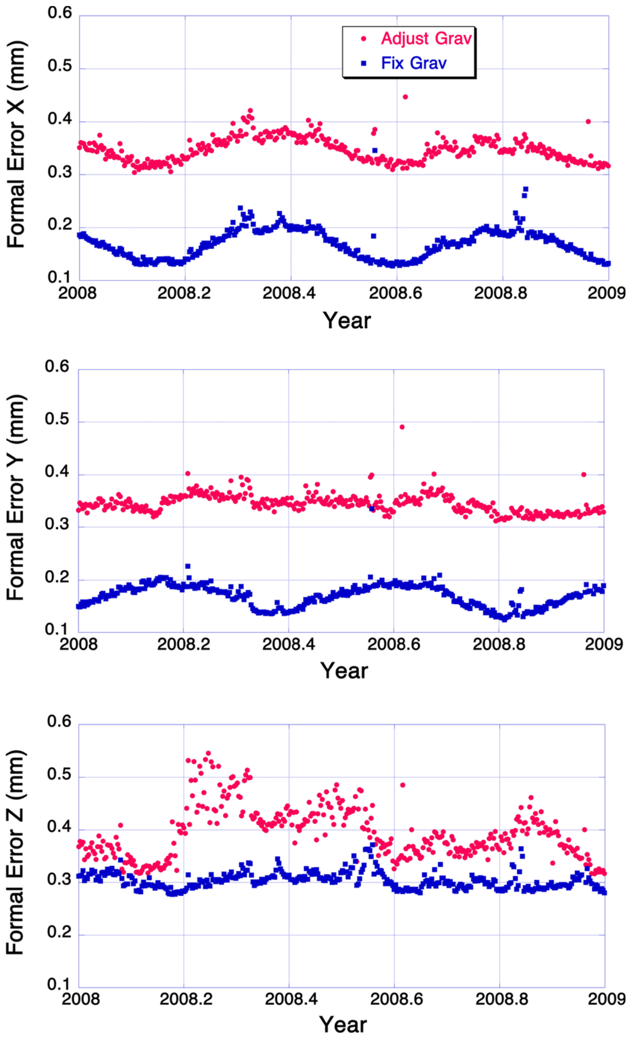

Fig. 5 Formal error change due to the estimation of gravity field. Fixing the gravity field and estimating the gravity field are shown in blue and red, respectively

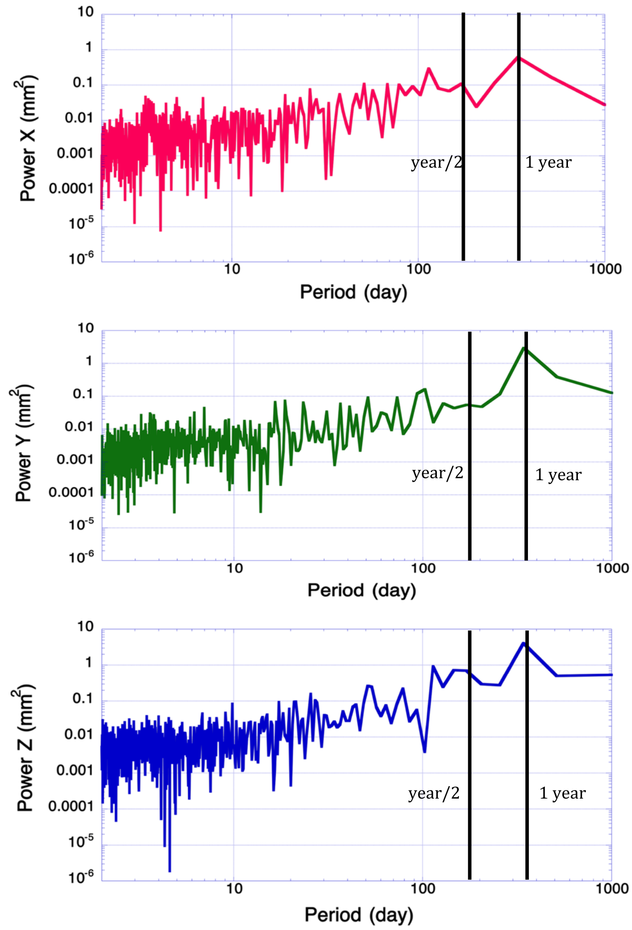

Fig. 6 Power spectrum of the estimated geocenter motion time series

characterize the estimates from our daily solution, analysis of the estimated time series can provide some information on the physical nature of the estimates. The Fast Fourier Transformation (FFT) of the 4-year time series of estimated geocenter motion (Fig. 6) shows a power-law like spectrum for all 3 components (for periods down to 10 days, at least). Even at the shortest periods (approaching 2 days), there is still some structure instead of pure white noise. However, the time series is not long enough to separate the annual (365-day) and the GPS draconitic periodic (351-day) periods.

The auto-correlation function, on the other hand, can yield fine time resolution through shifting the series at 1-day steps. As shown in Fig. 7, the X and Y components of the auto-correlation function clearly show correlation peaks away from the GPS draconitic period (351-day) and close to the annual period (365-day). The Z component shows a correlation peak deviated slightly away from annual (365-day) toward the GPS draconitic period (351-day), but is rather flat than dominant. Overall the dominant period of the estimated geocenter motion time series is annual. There is no sign of either GPS or GRACE draconitic period as dominant. Some signature of the GPS draconitic period exists and may affect the phase of the annual signal, but does not dominate the period. Had there been significant error in the GPS draconitic frequency present in any component, the 15 day/year phase drift away from the annual frequency would have accumulated to 60 days after the 4-years span of the estimates and been visually noticeable.

5 Summary

We developed a method to estimate the location of Earth's center of mass in the terrestrial reference frame on daily basis through single LEO POD using onboard GPS tracking data. Results from 4 years of GRACE GPS data and accelerometer data processing reveals seasonal geocenter motion variations that are comparable to monthly or weekly solutions from other techniques. Our approach has the potential to

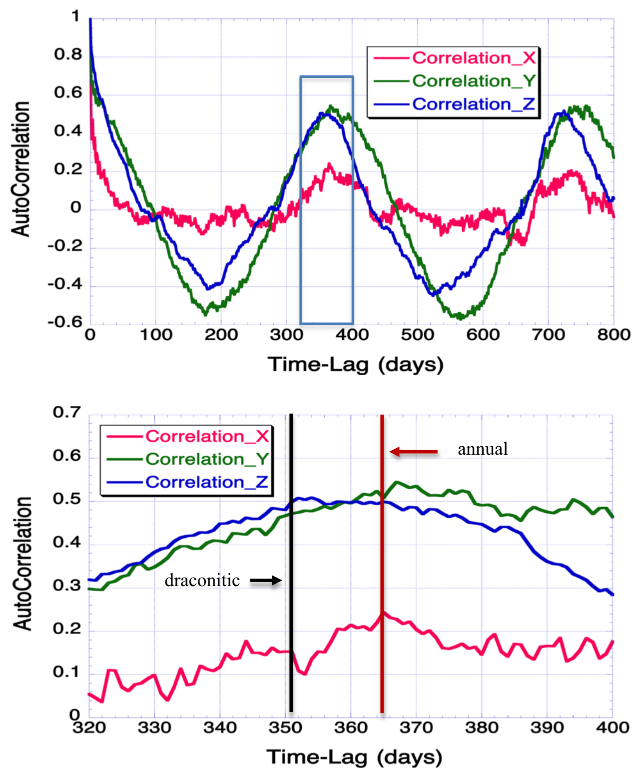

Fig. 7 Autocorrelation of the estimated geocenter motion time series, with the lower panel being the zoomed box shown in the upper panel

recover subseasonal variation of geocenter motion, which currently there is no sufficient way to validate. Although our method does not directly use any ground tracking stations in the process, we use the single-receiver ambiguity resolution technique to resolve the ambiguities for baselines between the LEO satellite and the ground stations that were used to generate the fiducial GPS orbit and clock product by JPL (Bertiger et al. 2010). The concept is similar to using double differenced GPS carrier phase measurements between the LEO and ground stations (Kang et al. 2009). The interferometric accuracy of the GPS carrier phase-measured evolving baselines between LEO satellites and ground stations enhances the sensitivity of the LEO GPS tracking to the Earth's center of mass. The continuous temporal resolution of multichannel tracking and the economic global spatial coverage makes it possible to estimate geocenter motion using LEO GPS tracking on a daily basis. The use of LEO accelerometer measurements to replace conventional non-gravitational force models overcomes the primary challenge for force modeling in geocenter determination using GPS tracking. Our results support the primary benefit that the GRASP mission concept is intended to provide, even with only a simplified version of the proposed configuration.

It should be pointed out that in our study we use the "fiducial" GPS orbit and clock product created at JPL, in which a selected ground network is fixed to IGS14 specified coordinates every day. In this way, the estimated frame shift is consistent with the conventional geocenter definition of CM-CN. If different GPS orbit and clock products are used, e.g., the "no-net-rotation" or "no-net-translation" product, the estimated frame shift would be different and may not agree with the geocenter motion determined from other techniques correspondingly.

Part of the existing errors of the fixed-GPS satellite orbit and clock strategy presented here comes from the realization error in IGS14 provided by the associated product due to the change in the selection of ground network and change of the real station positions (away from IGS14 definition) from day to day. While theoretically the reference frame is changed in the LEO POD with the estimated geocenter location we keep the clock parameters in the GPS product (which is a part of the frame definition package) unchanged in the POD processing. This approach may introduce some inconsistency. These errors are expected to be reduced or to vanish if the GPS orbits and clocks are solved simultaneously with GRACE satellite orbits using a ground network configuration carefully maintained from day to day. In particular helpful in averaging out systematic errors is to include multiple LEOs together in the overall solution. Such experiments are beyond the scope of this paper.

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Author contribution Da Kuang formulated the algorithm, processed the data, and drafted the article. Willy Bertiger developed the analysis tools to enable dynamic GRACE POD using accelerometer data for this study. Shailen Desai conceived the plan to determine the time-varying gravity simultaneously to separate the largest perturbing force and provided inputs to the article. Bruce Haines performed research on the error in reference frame dissemination through GPS products, validated the results and provided inputs to the article. Dah-Ning Yuan performed research on various parameterizations for dynamic GRACE POD using accelerometer data.

Data availability The raw data required to reproduce the results in this paper are available from "GRACE LEVEL 1B JPL RELEASE 3.0" through the Physical Oceanography Distributed Active Archive Center (PODAAC) Web site: https://podaac.jpl.nasa.gov/dataset/GRACE_L1B_GRAV_JPL_RL03. The JPL fiducial-fixed-GPS orbit and clock product are available from the Web site https://sideshow.jpl.nasa.gov/pub/JPL_GPS_Products/Final.

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