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ORIGINAL ARTICLE

Geocenter variations derived from GPS tracking of the GRACE satellites

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Abstract Two 4.5-year sets of daily geocenter variations have been derived from GPS-LEO (Low-Earth Orbiter) tracking of the GRACE (Gravity Recovery And Climate Experiment) satellites. The twin GRACE satellites, launched in March 2002, are each equipped with a BlackJack global positioning system (GPS) receiver for precise orbit determination and gravity recovery. Since launch, there have been significant improvements in the background force models used for satellite orbit determination, most notably the model for the geopotential, which has resulted in significant improvements to the orbit determination accuracy. The purpose of this paper is to investigate the potential for determining seasonal (annual and semiannual) geocenter variations using GPS-LEO tracking data from the GRACE twin satellites. Internal comparison between the GRACE-A and GRACE-B derived geocenter variations shows good agreement. In addition, the annual and semiannual variations of geocenter motions determined from this study have been compared with other space geodetic solutions and predictions from geophysical models. The comparisons show good agreement except for the phase of the z-translation component.

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1 Introduction

The geocenter is the center of mass (CM) of the whole Earth system, including the solid earth, ocean, atmosphere, hydrosphere, and cryosphere. Mass redistribution in the Earth system causes geocenter motion. To describe geocenter motion, a terrestrial reference frame, where the center of figure (CF) of the solid Earth is adopted as the origin of the frame, is needed. There are two established definitions to show the geocenter motion (Dong et al. 2003). One is the vector offset of CF relative to CM and the other is the reverse: the vector offset of CM relative to CF. Obviously, their amplitudes are the same and their phases differ by 180°. Here, we define the geocenter as CF relative to CM.

Observations of geocenter motion are fundamental to defining the origin of the International Terrestrial Reference Frame (ITRF) and investigating the mass transport of the whole Earth system. The geocenter translation is relative to the origin of the terrestrial reference frame defined by a network of crust-fixed tracking stations. The resulting geocenter motion can be observed by space geodetic techniques in two ways: by measuring the translation of the tracking network relative to the center of the geodetic satellite orbits or inferred by observing the deformation of the solid Earth due to the surface mass load. Space geodetic techniques, such as satellite laser ranging (SLR), Doppler Orbitography and Radiopositioning Integrated on Satellite (DORIS), and global positioning system (GPS), have demonstrated that the geocenter moves a few millimeters relative to the ITRF over timescales ranging from diurnal and semidiurnal (Watkins and Eanes 1997) to seasonal (e.g., Chen et al. 1999).

Seasonal geocenter motion can also be predicted based on geophysical models for the mass redistribution in the oceans, atmosphere and land water. The comparison of the two types of measurements can be used to assess the observed results and to evaluate the geophysical models.

In recent years, a number of studies have shown good agreement between space geodetic solutions and geophysical model predictions (Dong et al. 1997; Ray 1999; Chen et al. 1999; Bouille et al. 2000; Blewitt et al. 2001; Dong et al. 2003; Wu et al. 2006; Lavallee et al. 2006). The annual components from SLR tracking generally match the geophysical prediction in both amplitude and phase. DORIS-based solutions are in good agreement with the SLR solutions except for the amplitude of the y-component. The amplitude of the geocenter motion from GPS is generally larger than the other estimates, except for Wu et al. (2006) (in which the GPS displacement series was augmented by ocean bottom pressure (OBP) from a data-assimilating ocean circulation model). The summary of the annual geocenter motion derived from SLR, DORIS and GPS is given by Dong et al. (2003).

Current methods to observe geocenter typically consider either the translational or deformation effect on the CM due to the surface load. Most published results of the geocenter motion derived from GPS are obtained by processing the ground-based tracking of the GPS satellites and observing the surface deformation. While only the degree-one deformation (the deformation due to the degree-one mass change) is the desired signal, higher degree deformation can alias the estimates and should also be estimated or provided from an external source (Wu et al. 2006; Lavallee et al. 2006). However, a unified approach that considers both the translational and deformation of the GPS network has also been tested recently (Lavallee et al. 2006). With improved background force models used for satellite orbit determination, most notably the model for the geopotential, the question is whether the GPS-LEO tracking to the GRACE satellites (Tapley et al. 2004) can provide estimates of the geocenter motion based on the translational effect, in a manner similar to DORIS and SLR.

In the following, the methods for geocenter motion determination are discussed, and the processing of the GPS-LEO tracking of the GRACE satellites is described. The results of the GPS-LEO GRACE solutions are then presented and compared with other space geodetic solutions and predictions from geophysical models.

2 Techniques and methods for determination of geocenter motion

GPS-LEO, DORIS and SLR are all based on processing data from relative low altitude satellites for estimation of the geocenter motion vector. However, the ground GPS is based on the information from high altitude GPS satellites. Geocenter motion has been observed using SLR and DORIS tracking to LEO satellites, but to date, GPS tracking to LEO satellites has not been employed similarly. The GPS-LEO tracking system consists of three elements; the GPS constellation, the GPS onboard receiver in low Earth orbit (500–1,300 km altitude), and the GPS ground station network (Kang et al. 1997). There are three different methods that can be used for determining the translational effect of geocenter motion using GPS-LEO data: geometric, kinematic and dynamic methods. Each method will be affected differently by the various error sources, and the optimal method for any particular tracking data type will depend on the nature of the satellite orbit errors, the tracking data errors, and the distribution of the ground network.

The geometric method (network shift method) obtains a free-network solution in a CM frame, and performs a time series of seven-parameter (Helmert) transformations relative to some long-term mean reference network (Bouille et al. 2000; Dong et al. 2003). The estimated translation parameters represent the geocenter motion. The inclusion of a scale parameter in the Helmert transformation may, however, be unnecessary and may result in undesirable correlations with the translational parameters (Lavallee et al. 2006).

The dynamic method uses the fixed reference frame to directly estimate degree-one geopotential Stokes coefficients based on the observed satellite orbit perturbations. If tracking data from only one satellite is used, estimates for geocenter motions will represent linear combinations of several low degree and order Stokes coefficients, not just the degree-one coefficients (Kar 1997). Tracking data from several different satellites may be required for this method, or the GRACE mission gravity estimates can be used for the coefficients above degree one. It is noted that with this approach, the CM of the Earth is no longer the origin for the orbit dynamics, and additional Coriolis-type terms must be included in the numerical orbit integration to be fully consistent (Kar 1997).

Finally, the kinematic method directly estimates the geocenter vector offset between the CM and CF using satellite tracking data. This method estimates only three geocenter offset coordinates, not a whole network of station coordinates, but it is susceptible to errors in the reference frame, which is held fixed.

In addition, all three methods depend on the accuracy of the modeling of station displacements and adopted kinematic model on the realized ITRF origin. Although the globally averaged deformation is small, those approaches ignore the quite large deformations that occur at each site (Lavallee et al. 2006). For our investigation, we have used the kinematic method.

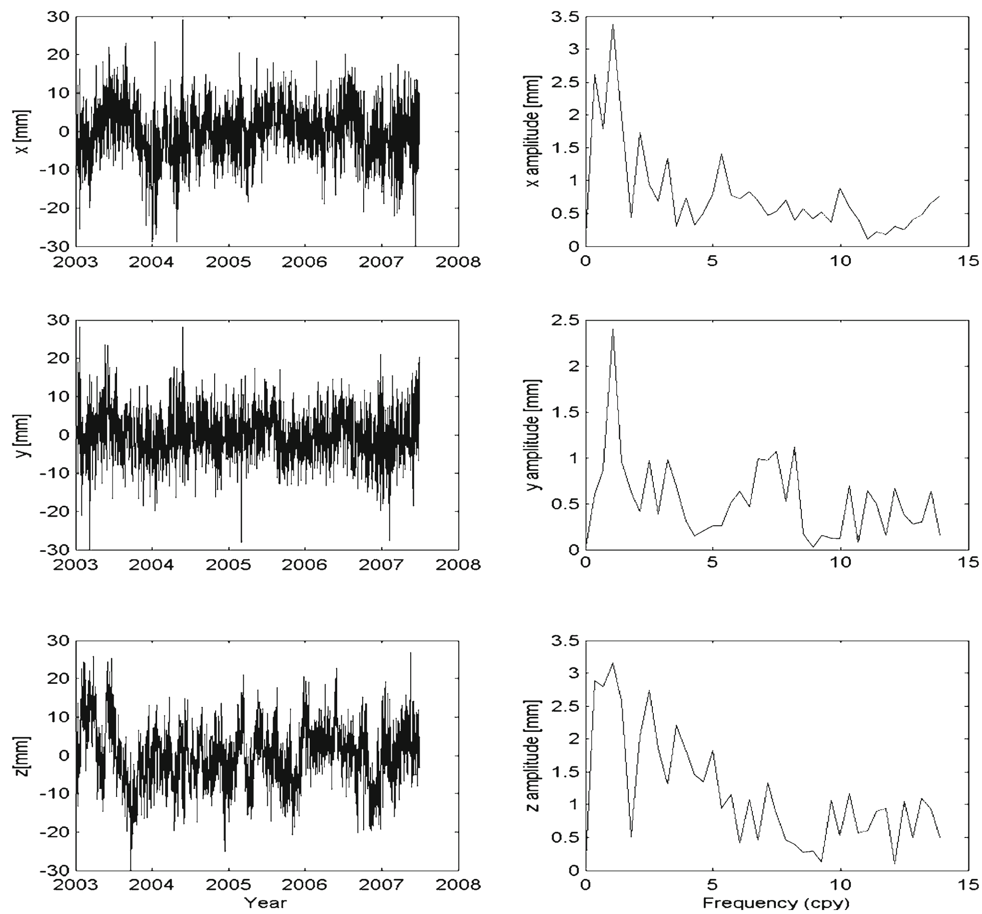

Fig. 1 Daily geocenter time series and power spectrum for each geocenter component derived from GRACE-A

3 Data processing

For this study, the GPS tracking of the GRACE satellites has been used. The GRACE mission is a joint project between the National Aeronautics and Space Administration (NASA) and the Deutsches Zentrum für Luft- und Raumfahrt (DLR). The primary objective of the GRACE mission is to map, with unprecedented accuracy, the long- to medium-wavelength spherical harmonic coefficients of the Earth's gravity field and to observe its temporal variations (Tapley et al. 2004). The twin GRACE satellites (GRACE-A and GRACE-B) were launched on March 17, 2002 into near polar orbits with an initial altitude of about 500 km. For the precise orbit determination (POD) and gravity field recovery, both GRACE satellites are equipped with several scientific instruments: a BlackJack GPS onboard receiver, a SuperSTAR accelerometer, a star tracker, a K-Band Ranging (KBR) system and a SLR retroreflector. The BlackJack receiver (Dunn et al. 2003) is an advanced codeless, dual-frequency flight GPS receiver developed by the Jet Propulsion Laboratory (JPL).

The GRACE GPS data are processed in the form of double-differenced (DD) carrier-phase converted range measurements using a network of 51 International GNSS Service (IGS) (Beutler et al. 1999) ground stations. These sites were selected based on the IGS reported station performance and their good geographical distribution (Ferland et al. 2001). The IGS realization of ITRF2000 (IGb00) is used for the ground station coordinates. The IGS final orbits of the GPS satellites are also used in our GPS data processing, although corrections to selected orbital elements (eccentricity, inclination, argument of perigee and longitude of ascending node) are estimated to accommodate the residual GPS satellite orbit errors (Rim 1995). The orbit processing was performed using the Center of Space Research (CSR) Multi-Satellite Orbit Determination Program (MSODP), which is based on a dynamic orbit determination method utilizing the batch processing approach (Rim 1992). The data used are GRACE level 1B products produced by the NASA JPL (Case et al. 2004).

For estimation of the geocenter vector (CM relative to CF), our data processing is based on the dynamic orbit determination for GRACE orbits and in form of DD carrier-phase observations by fixing GPS orbits. Therefore, the GPS ground stations are used to define CF; GRACE dynamic orbits are used to define CM. The GPS satellites are treated as space geometric objects; the GRACE satellites are considered as dynamic objects which move around the geocenter. And the GPS satellite orbits have the same reference system as the ground stations. Because the IGS GPS orbits have errors,

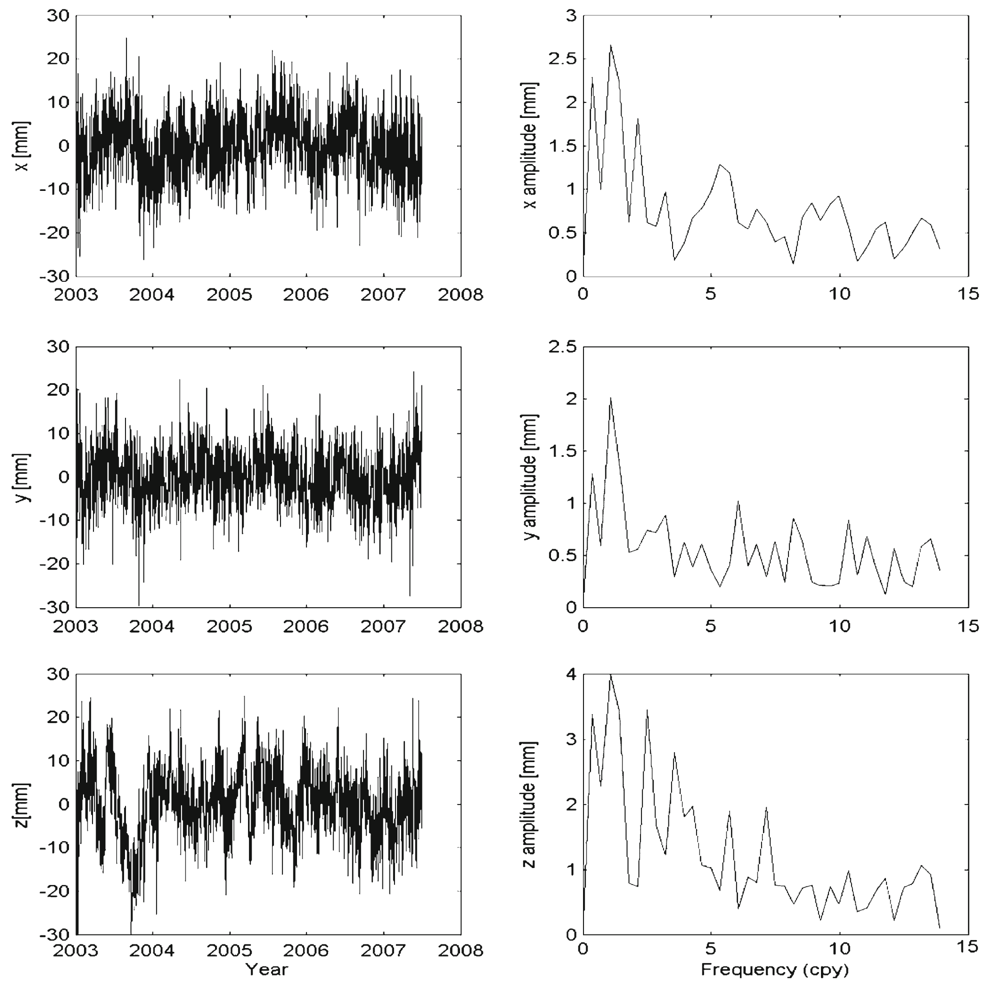

Fig. 2 Daily geocenter time series and power spectrum for each geocenter component derived from GRACE-B

estimation of the corrections can improve the accuracy of GRACE orbits (Kang et al. 2006).

For a typical daily solution using the kinematic method, the estimated parameters include not only three geocenter *x*-, *y*- and *z*-components, but also GRACE initial position and velocity, GPS DD phase ambiguities for each pass, zenith delay parameters every 30 min, once-per-revolution empirical acceleration parameters (once every orbit revolution for the along-track and cross-track components). A more detailed description of the GRACE data processing is given by Kang et al. (2006).

4 Results and discussion

The GRACE GPS data from January 1, 2003 to June 30, 2007 were processed in daily orbit fits for estimating the geocenter variations using the kinematic method. Figures 1 and 2 show daily geocenter time series and their spectra, derived from GRACE-A and B, respectively. Figures 3 and 4 show the GRACE-derived monthly averaged geocenter time series and spectrums (using 30-day moving average). As expected, the main part of the time series appears at the 1-cpy (cycle per year) frequency, which is believed to be driven by seasonal mass redistribution within the Earth system (e.g., Dong et al. 1997; Chen et al. 1999). The spectra show other frequencies, but they do not agree well between different components and probably do not represent real geophysical signals. There are no significant differences for the annual geocenter motion derived from the daily or monthly average time series.

By comparing Fig. 1 with Fig. 2, as well as Fig. 3 with Fig. 4, we see that the time series and spectra derived from GRACE-A and GRACE-B are very similar. Because they are based on the same GPS orbits, GPS ground stations and processing models, it is not surprising that they agree well. The amplitudes of the annual signal for all three components are in the range of 2–4 mm. In order to determine the amplitude and phase of the annual and semiannual signals, a least-squares polynomial and trigonometric function fitting has been used. The fitting equation is:

$$C(t) = \sum_{i=1}^{n} A_i \sin\left[\frac{2\pi}{P_i}(t - t_0) + \phi_i\right] + b_0 + b_1(t - t_0) \quad (1)$$

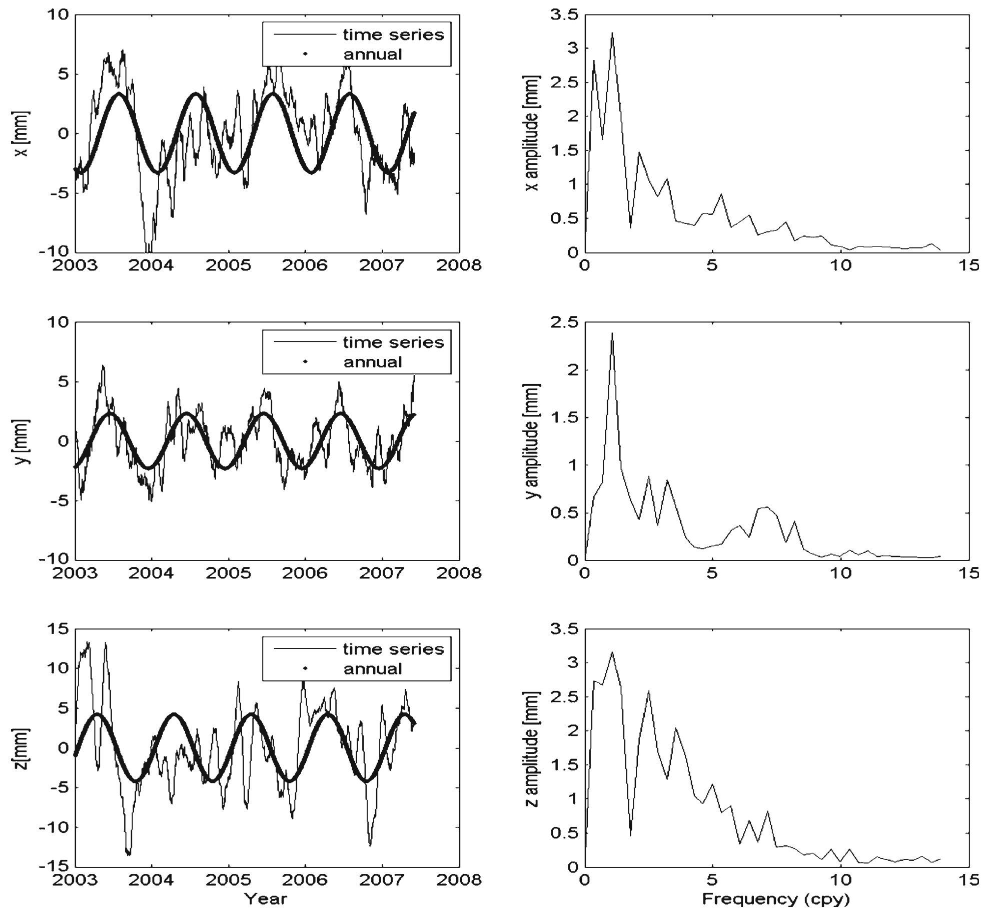

Fig. 3 Monthly (30-day moving) average geocenter time series, annual curve fit and power spectrum derived from GRACE-A

where A_i is amplitude; P_i is period; ϕ_i is phase in degree; t_0 is 1 January; b_0 is bias and b_1 is trend.

Table 1 lists some observed annual geocenter variations derived from SLR, DORIS, GPS and GPS-LEO and geophysical model predictions from surface mass redistribution. The GPS-LEO results are comparable to the other space-based solutions and geophysical model predictions except for the phase in the z-direction. Both the amplitude and phase in x- and y-components of the GPS-LEO estimates lie between model-predicated annual variations.

The solutions from GRACE-A and GRACE-B in Table 1 can be used to indicate the internal agreement, which is very good. The geocenter motion amplitude differences between GRACE-A and GRACE-B range from 0.1 to 0.6 mm; the phase differences range from 3° to 12°. The difference in the estimates from GRACE-A and GRACE-B are at the same level as the formal uncertainties and likely represent only a lower limit to the actual uncertainty; they do not provide the information on the systematic error effects since the processing methods and models are identical. The differences between the various space geodetic solutions and geophysical model predictions provide a better sense of the true uncertainty. The external agreements for GPS-LEO GRACE solutions in Table 1 are reasonably good in x- and y-components. Both amplitude and phase derived from GPS-LEO are within the range of geophysical model predictions and closer the SLR solutions. The amplitude of the GPS-LEO z-component is little larger than that from SLR, but much smaller than those from ground GPS solutions. The phase differences between GPS-LEO and SLR solutions as well as model predictions in the z-component can be more than 100°. The solutions from GPS-LEO are generally better than those from GPS-only, as compared to SLR estimates and geophysical model predictions, especially in the x- and y-component. Zhu et al. (2004) came up with nearly the same statement based on four arc tests. Unknown systematic errors appear to mostly affect the z-component of GPS-LEO solutions.

Table 2 lists the observed and predicted semiannual variations of geocenter motion derived from SLR and GPS-LEO GRACE data as well as from model predictions based on surface mass redistribution. The agreement between GPS-LEO and SLR as well as the model predictions are generally good (again except for the z-component). But the GPS-LEO solutions are closer to model predictions for both amplitude and phase. The semiannual amplitudes of the GPS-LEO z-components are somewhat larger than those

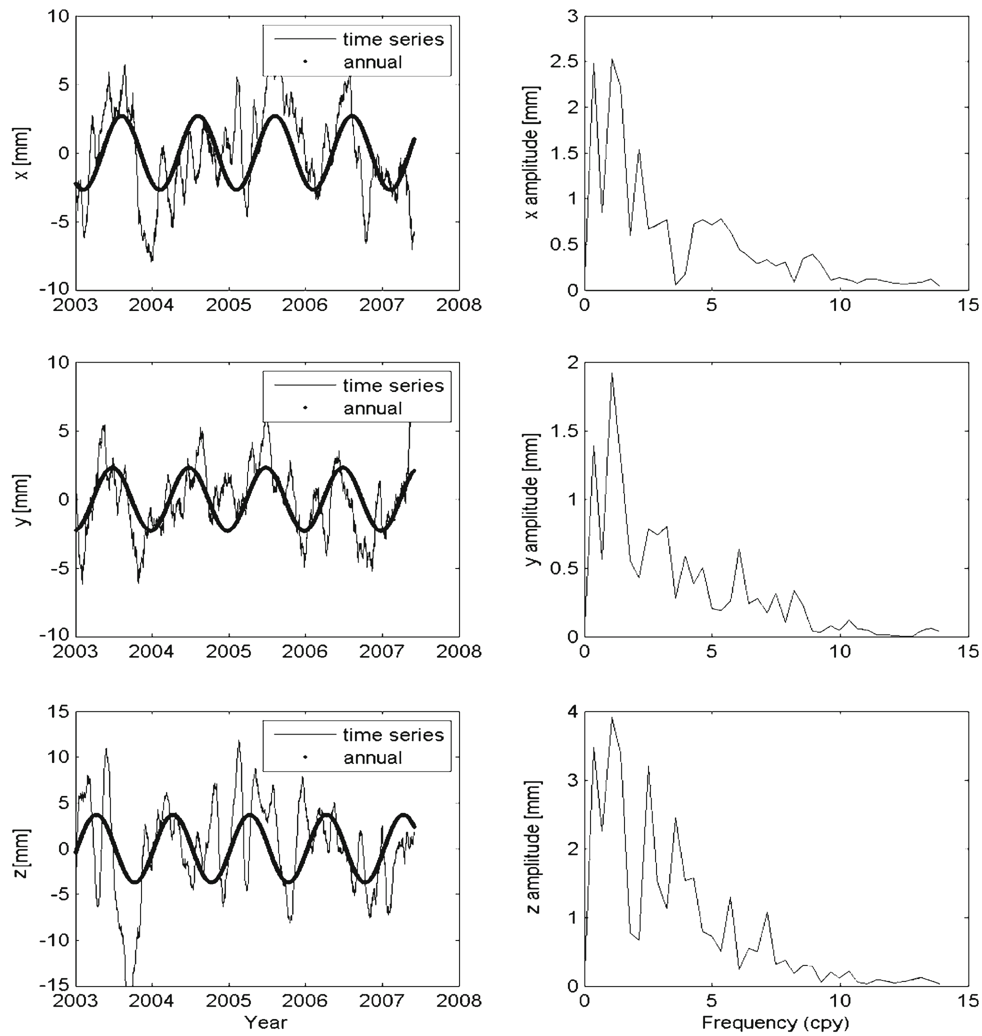

Fig. 4 Monthly average geocenter time series, annual curve fit and power spectrum derived from GRACE-B

Table 1 Observed and predicted annual component of geocenter motion

	x		*y*		*z*	
	Amplitude (mm)	Phase (deg)	Amplitude (mm)	Phase (deg)	Amplitude (mm)	Phase (deg)
LAGEOS 1 & 2 (Eanes et al. 1997)	2.2	211	3.2	331	2.8	225
LAGEOS 1 & 2 (Bouille et al. 2000)	2.1 ± 0.5	223	2.0 ± 0.5	308	3.5 ± 1.5	228
DORIS (Bouille et al. 2000)	1.8	205	5.0	349	3.0	298
GPS/OBP (Wu et al. 2006)	1.7	274	3.8	285	4.5	249
GPS (Blewitt et al. 2001)	3.3 ± 0.3	184	4.8 ± 0.3	285	11.0 ± 0.2	214
GPS (Dong et al. 2003)	4.8 ± 0.4	220 ± 5	3.6 ± 0.4	320 ± 7	9.4 ± 0.5	105 ± 3
GPS GRACE-A (this study)	3.3 ± 0.2	244 ± 14	2.4 ± 0.2	286 ± 14	4.2 ± 0.3	344 ± 16
GPS GRACE-B (this study)	2.7 ± 0.2	232 ± 14	2.3 ± 0.2	277 ± 14	3.7 ± 0.3	349 ± 16
Predicted (Dong et al. 1997)	4.2	224	3.2	339	3.5	235
Predicted (Chen et al. 1999)	2.4	244	2.0	270	4.1	228
Predicted (Bouille et al. 2000)	1.6	236	1.8	309	3.1	254

from model predictions. However, the phase agreements are fairly good. In addition, the differences between the two sets of model predictions (i.e., Dong et al. 1997 vs. Chen et al. 1999) are significant at the semiannual period (the amplitude differences are from 0.1 to 0.6 mm; the phase differences are from 9° to 96°). In general, the agreement between observed

Table 2 Observed and predicted semiannual component of geocenter motion

	x		*y*		*z*	
	Amplitude (mm)	Phase (deg)	Amplitude (mm)	Phase (deg)	Amplitude (mm)	Phase (deg)
Lageos 1 & 2 (Eanes et al. 1997)	1.1	344	0.8	33	0.4	193
GPS GRACE-A (this study)	0.6 ± 0.3	350 ± 8	0.7 ± 0.2	117 ± 8	1.6 ± 0.3	52 ± 8
GPS GRACE-B (this study)	1.0 ± 0.3	352 ± 8	0.7 ± 0.2	87 ± 8	1.3 ± 0.3	74 ± 8
Predicted (Dong et al. 1997)	0.6	352	0.4	97	1.1	142
Predicted (Chen et al. 1999)	0.7	1	0.9	41	0.5	58

and predicated variations of geocenter motion is not good in the semiannual period and for z-component.

5 Conclusions

Accurately determined geocenter variations provide important information about mass redistribution in the Earth system. This study has demonstrated that using a kinematic approach with GPS-LEO tracking to the GRACE satellites can be effective in observing annual and semiannual variations in geocenter motion. The estimated annual and semiannual variations are in good agreement in both amplitude and phase with the SLR solution and predicted values from geophysical models except for the phase of the z-component. The GPS-LEO solutions appear consistent with geophysical model predictions and have small differences with SLR solutions. Generally, the results from the GPS-LEO GRACE are competitive, as compared with other approaches. In the future, longer GPS-LEO data from multiple satellites may further improve the accuracy for geocenter variation determination.

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