Geocenter motion estimated from GRACE orbits: The impact of F10.7 solar flux

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Abstract

We assess the impact of orbit modeling on the origin offsets between GRACE kinematic and reduced-dynamic orbits. The origin of the kinematic orbit is the center of IGS network (CN), whereas the origin of the reduced-dynamic orbit is assumed to be the center of mass of the Earth (CM). Theoretically, the origin offset between these two orbits is associated with the geocenter motion. However, the dynamic property of the reduced-dynamic orbit is highly related to orbit parameterizations. The assessment of the F10.7 impact on the geocenter motion is implemented by using different orbit parameterization setups in the reduced-dynamic method. We generate two types of reduced-dynamic orbits using 15 and 240 empirical parameters per day from 2005 to 2012. The empirical parameter used in Bernese GNSS Software is called piece-wise constant empirical acceleration (PCA) and is mainly to absorb the non-gravitational forces mostly related to the atmospheric drag and solar radiation pressure. The differences between kinematic and dynamic orbits can serve as a measurement for geocenter. The RMS value of the geocenter measurement in the 15-PCA case is approximately 3.5 cm and approximately 2 cm in the 240-PCA case. The correlation between the orbit difference and F10.7 is about 0.90 in the 15-PCA case and ~0.10 to 0 in the 240-PCA case. This implies that the reduced-dynamic orbit modeled with 240 PCAs absorbs the F10.7 variation, which aliases to the 15-PCA orbit solution. The annual amplitudes of the geocenter motion are 3.1, 3.1 and 2.5 mm in the 15-PCA case, compared to 0.9, 2.0 and 1.3 mm in the 240-PCA case in the X, Y and Z components, respectively. The 15-PCA solution is thus closer to the geocenter motions derived from other space-geodetic techniques. The proposed method is limited to the parameterizations in the reduced-dynamic approach.

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Keywords: GPS; GRACE; Geocenter motion; Solar activity; F10.7

1. Introduction

On long time scales, the Earth’s center of mass (CM or geocenter) is positioned at an ideal origin of a conventional terrestrial system (CTS), which is typically realized by a network of stations equipped with sensors providing long-term observations of Earth-orbiting satellites or celestial objects. However, geocenter moves with respect to the...
origin of the CTS, because of the mass re-distribution and deformation of the Earth’s surface. Without proper modeling, such a geocenter motion may result in misinterpretations of data that require a precise, consistent, and stable reference frame.

To date, geocenter motion is mainly determined using a number of geodetic techniques, such as Satellite Laser Ranging (SLR) to geodetic satellites, microwave observations from Global Navigation Satellite Systems (GNSS) or Doppler Orbitography and Radiopositioning Integrated by Satellite (DORIS), which can be confirmed with respect to the geophysical models. A summary of these techniques can be found in Lavallée et al. (2006) and Wu et al. (2012). Space-geodetic techniques determine geocenter motion based on three major methods: (1) orbit dynamics, (2) surface loading displacements and (3) datum transformation.

By the first method, the geocenter is equivalent to degree-one coefficients of the Earth’s gravity field. Such coefficients are part of the parameters estimated in the dynamic orbit solution of the motion equations of an artificial satellite around the Earth (Seeber, 2003). Examples based on orbit dynamics are described by Kang et al. (2009) and Cheng et al. (2010). By the second approach, the geocenter motion is directly related to the surface mass redistribution and thus can be recovered from the surface load displacements, e.g., of GPS stations (e.g., Blewitt and Clarke, 2003; Rietbroek et al., 2009; Collilieux et al., 2012). In the third approach, the geocentric position is the geometric translation vector that is part of the parameters defining the two reference frames: One is in a well-established reference frame based on long-term precise observations, e.g., IGS08 and ITRF2008 (Altamimi et al., 2011). The second frame is realized through instantaneous positions of fiducial stations determined using satellite observations from daily or weekly batches. In such a case, the origin of the well-established frame defines the center of IGS network (CN), whereas the instantaneous positions of fiducial stations represent the center of mass (CM) frame. Examples based on datum transformation are described by Bouille et al. (2000), Lavallée et al. (2006) and Collilieux et al. (2009, 2010).

In this study, we introduce a concept that regards a low Earth orbiter (LEO) as a probe for the recovery of geocenter motion. Theoretically, all satellites are sensitive to the geocenter motion. However, due to various methods of the orbit determination, some orbital positions can be expressed in the CN frame, e.g., positions of GNSS satellites, whereas some orbits can be integrated around the instantaneous Earth’s CM frame. In our approach, we assume that the pure geometry of the observations provides the CN, whereas the orbit dynamics provides information on CM.

First, the coordinates of the LEO are determined by the so-called GPS-based kinematic orbit determination (KOD). We use the GPS orbits provided by Center of Orbit Determination in Europe (CODE), which are integrated in CN, i.e., around the origin of IGS08 reference frame. The resulting LEO kinematic positions are purely geometric as they are directly defined by geometric GPS-LEO ranging measurements in a coordinate reference frame with the origin being the CN.

In the second stage, we determine the continuous LEO orbits in the so-called reduced-dynamic orbit determination (DOD) procedure. However, the determination of reduced-dynamic orbits is typically associated with a number of empirical parameters estimated in orbit determination. The empirical parameter used in Bernese GNSS Software (as a tool used in this study) is called piece-wise constant empirical acceleration (PCA) (Dach et al., 2015). Thus, we give “more flexibility” to the orbital motion and thus allow the LEO to orbit the instantaneous Earth’s CM.

The current ITRF (e.g., ITRF2008) is derived from multi-year combinations of SLR, VLBI, GPS and DORIS solutions. It is more likely a long-term realization of CN frame, which is approximately equivalent to the long-term realization of CM frame. This means that such a frame contains only the linear motion and neglects seasonal and short-term motions. Meanwhile the DOD solutions (assuming no errors) are related to an instantaneous CM frame (including both long-term and short-term geocenter motions). Thus, the differences between KOD and DOD solutions reflect the short-term geocenter motions (mostly seasonal).

The objectives of this paper are twofold: (1) demonstration of the concept of the geocenter motion estimation using GRACE precise orbits and (2) showing the effects of the solar activities indexed by F10.7, not only on the orbit parameterization but also on estimations of geocenter motion. Because the origin of satellite orbit plane is strongly affected by orbit dynamic modeling, we design two testing dynamic orbits derived from different non-gravitational models and separately compare them with the kinematic orbit. The description of estimating the geocenter motion using the LEO satellite is given in Section 2. The orbit difference in this study is regarded as the measurement for geocenter and the impact of F10.7 on the orbit difference is emphasized in Section 3. We also present a comparison of geocenter-motion solutions derived by different space geodetic techniques, e.g., SLR and geophysical prediction models in Section 4. A summary and the conclusions based on the results are provided in Section 5.

2. LEO as a probe for measuring geocenter motion

2.1. Concept of a LEO probe

In the datum transformation method, the geocenter motion estimation is sensitive to the distribution of stations (Tregoning and van Dam, 2005) and models used for the dynamic orbit. Here, we estimate the geocenter motion by treating the LEO as an orbiting probe. This method is similar to that used by Melachroinos et al. (2013). Because the LEO’s trajectory can cover within a short time a large
part of the Earth over both land and oceans, the number of geometric translations increases dramatically. For example, at a 0.1 Hz sampling rate, each of the twin GRACE satellites collects 8640 sets of measurements for estimating translation parameters in a day and the measurements are almost uniformly distributed over the entire Earth, thanks to the 89° orbit inclination angle of GRACE. The geometry for the geocenter motion estimation using LEO is presented in Fig. 1.

As shown in Fig. 1, the GRACE satellite is considered as a probe whose orbits can be determined in both KOD and DOD. The reduced-dynamic orbit $r_{\text{DYN}}$ results from the solution of the motion equations of an Earth-orbiting satellite in the CM frame. The kinematic orbit $r_{\text{KIN}}$ is given in the CN frame, which is defined by the IGS ground network provided by CODE products. The CN is used in this study, instead of the center of the figure (CF).

The difference between CN and CF, called the “network effect”, can be estimated to 1-mm level accuracy using a network consisting of 30 stations (Collilieux et al., 2009). The final GPS orbit product used in this study is estimated using 270 ground stations evenly distributed over the world, according to a documentation of CODE analysis strategy summary (ftp://ftp.unibe.ch/aiub/CODE/0000_CODE.ACN). This suggests that the CN is very close to the CF and we thus define our geocenter motion CM–CN to approximate the CM–CF.

By the proposed method, one firstly computes both the kinematic orbit and the reduced-dynamic orbit of a LEO at a given epoch and the orbit difference is attributed to the geocenter motion perturbation. Using the notations in Fig. 1, the observation equations in the matrix representation for the least-squares estimation of the transformation parameters are

$$ V = B\xi - (r_{\text{KIN}} - r_{\text{DYN}}), $$

with

$$ B = \begin{pmatrix} 1 & 0 & 0 & 0 & -z_{\text{DYN}} & x_{\text{DYN}} & x_{\text{DYN}} \\ 0 & 1 & 0 & z_{\text{DYN}} & 0 & -x_{\text{DYN}} & y_{\text{DYN}} \\ 0 & 0 & 1 & -y_{\text{DYN}} & x_{\text{DYN}} & 0 & z_{\text{DYN}} \end{pmatrix} $$

and

$$ \xi = (\Delta X_{\text{geo}}, \Delta Y_{\text{geo}}, \Delta Z_{\text{geo}}, \alpha, \beta, \gamma, u)^T, $$

where $B$ is the design matrix formed by the partial derivatives with respect to the seven transformation parameters assuming small rotation angles, the position vector $(x_{\text{DYN}}, y_{\text{DYN}}, z_{\text{DYN}})^T$ denotes a reduced-dynamic orbit, $\xi$ is a vector containing unknown parameters, including three translations (geocentric position $(\Delta X_{\text{geo}}, \Delta Y_{\text{geo}}, \Delta Z_{\text{geo}})^T$, three rotation angles $(\alpha, \beta, \gamma)$, and a scale factor $u$, and $V$ denotes the noise.

Provided that the orbit difference components in $(r_{\text{KIN}} - r_{\text{DYN}})$ are uncorrelated and their errors are normally-distributed, the solution of $\boldsymbol{\xi}$ is

$$ \xi = (B^TB)^{-1}B^T(r_{\text{KIN}} - r_{\text{DYN}}). $$

The orbit difference $(r_{\text{KIN}} - r_{\text{DYN}})$ in Eq. (2) is regarded as the measurement for the geocenter.

2.2. Error budgets for KOD

To use a LEO as a probe for the recovery of geocenter motion, the first step is to compute the kinematic orbits (coordinates) of the LEO. Here, the ionosphere-free linear combination of GPS dual frequency observations $L_{\text{IF}}$ is used in the KOD to minimize the ionosphere effect and is expressed by

$$ L_{\text{IF}} = \left( \|r_{\text{ANT LEO}} - r_{\text{GPS}}\|^2 \right)^{1/2} + c \cdot (dt - dT) + \lambda_{\text{IF}} \cdot N_{\text{IF}} + \varepsilon, $$

where $r_{\text{ANT LEO}}$ denotes the position vector of the precise orbit determination (POD) antenna phase center; $r_{\text{GPS}}$ denotes the position vector of the antenna phase center of the GPS satellite; $c$ is the speed of light; $dt$ and $dT$ denote the receiver clock and GPS clock, respectively; $\lambda_{\text{IF}} \cdot N_{\text{IF}}$ is associated with the ambiguity resolution; and $\varepsilon$ is the noise of $L_{\text{IF}}$. In KOD, we used the so-called precise point positioning (PPP) strategy for orbit determination, for which both the GPS orbit and the clock are essential elements in Eq. (3). Thus, by fixing the GPS orbit and clock in Eq. (3), the $r_{\text{ANT LEO}}$ is directly defined in the CN frame, which is also the reference frame for the GPS orbit. Table 1 summarizes the GPS measurement models used for GRACE KOD in this paper.

The POD antenna’s position was first determined using PPP. Then, the kinematic orbit, referring to the satellite’s...
Table 1
Summary of GPS measurement and dynamic models used for GRACE orbit determination.

<table>
<thead>
<tr>
<th>Items</th>
<th>Model</th>
</tr>
</thead>
<tbody>
<tr>
<td>GPS measurement model</td>
<td>Zero-differenced ionosphere-free phase</td>
</tr>
<tr>
<td></td>
<td>GRACE PCOs + PCVs, iqs08.atx</td>
</tr>
<tr>
<td></td>
<td>CODE GPS final ephemerides and clocks</td>
</tr>
<tr>
<td></td>
<td>0.1 Hz sampling rate</td>
</tr>
<tr>
<td>Attitude information</td>
<td>GRACE star tracker quaternions</td>
</tr>
<tr>
<td>Gravitational models</td>
<td>EGM2008 (120 × 120)</td>
</tr>
<tr>
<td></td>
<td>Solid Earth, pole and ocean tides (IERS2010), FES2004</td>
</tr>
<tr>
<td></td>
<td>N-body effect (DE405)</td>
</tr>
<tr>
<td>Non-gravitational models</td>
<td>No air drag model</td>
</tr>
<tr>
<td></td>
<td>No radiation pressure model</td>
</tr>
<tr>
<td></td>
<td>Empirical parameters:</td>
</tr>
<tr>
<td></td>
<td>15 PCAs in RTN (for the 1st testing orbit)</td>
</tr>
<tr>
<td></td>
<td>240 PCAs in RTN (for the 2nd testing orbit)</td>
</tr>
<tr>
<td>Reference origin</td>
<td>CN for kinematic orbit</td>
</tr>
<tr>
<td></td>
<td>CM for dynamic orbit</td>
</tr>
</tbody>
</table>

Notes: a. Rebischung et al. (2012)  
b. Bock et al. (2009)  
c. Pavlis et al. (2012)  
d. Petit and Luzum (2010).  
e. Lyard et al. (2006)  
f. Standish (1998)  
g. Radial, tangential, normal.

2.3. Precise modeling in DOD

As opposed to the kinematic orbit, which is based on pure geometric observations, the reduced-dynamic orbit is subject to the force field of the entire Earth. By definition, the GRACE reduced-dynamic orbit, including its position and velocity, results from the solutions of the equations of motion in the CM frame:

\[
\mathbf{r}_{\text{DYN}} = -G M \mathbf{r}_{\text{DYN}} + \mathbf{f}_R(t, \mathbf{r}_{\text{DYN}}, \dot{\mathbf{r}}_{\text{DYN}}),
\]

where \(G M\) is the product of the gravitational constant and the Earth’s mass, \(\mathbf{r}_{\text{DYN}}\) is the vector from the geocenter to the center of the satellite’s mass, \(\mathbf{r}_R\) denotes the velocity vector of the satellite and \(\mathbf{f}_R\) denotes the perturbing forces.

In theory, the force parameters implied in \(\mathbf{f}_R\) along with the initial state vector, can be estimated by GPS observations. The perturbing forces in \(\mathbf{f}_R\) are

\[
\mathbf{f}_R = \mathbf{r}_{\text{lab}} + \mathbf{r}_{\text{se}} + \mathbf{r}_{\text{at}} + \mathbf{r}_{\text{air}} + \mathbf{r}_{\text{srp}},
\]

where \(\mathbf{r}_{\text{lab}}\) is mainly caused by the inhomogeneous mass distribution in the Earth; \(\mathbf{r}_{\text{se}}\) is caused by the gravitational attraction of the Sun, Moon and other planets, so-called the N-body effect; and \(\mathbf{r}_{\text{at}}\) and \(\mathbf{r}_{\text{air}}\) are mainly caused by the solid Earth tide and the ocean tide, respectively. They stem from the gravitation of the Sun and Moon, which cause additional perturbing forces acting on the satellite orbit; \(\mathbf{r}_{\text{srp}}\) is the force caused by solar radiation pressure (including the direct and Earth-reflected and emitted) effect; \(\mathbf{r}_{\text{air}}\) is caused by the atmospheric drag effect.

Table 1 summarizes the adopted perturbing force models for GRACE DOD. We used the EGM2008 (Pavlis et al., 2012) as the a priori Earth’s gravity field model for \(\mathbf{f}_R\). The DE405 (Standish, 1998) ephemeris was used for \(\mathbf{r}_{\text{lab}}\). The standards for models of \(\mathbf{r}_{\text{at}}\) and \(\mathbf{r}_{\text{air}}\) perturbing forces follow the recommendations of the IERS Conventions 2010 (Petit and Luzum, 2010). The acceleration vectors \(\mathbf{r}_{\text{at}}\) and \(\mathbf{r}_{\text{air}}\) result from surface forces acting on a satellite and require precise modeling of the satellite’s cross-sectional area, which is affected by the satellite attitude variations and the interaction between the satellite surface material and atmosphere molecules. We used the so-called piecewise constant acceleration (PCA) to handle both \(\mathbf{r}_{\text{at}}\) and \(\mathbf{r}_{\text{air}}\). The PCA are mainly used to model satellite’s velocity variations, caused by forces acting upon a satellite such as the atmospheric drag and solar radiation pressure, which lead to an instantaneous change of the accelerations.

If all of the gravitational forces are adequately modeled using the information in Table 1, the PCA parameters will compensate for the non-gravitational forces, as demonstrated by Jäggi et al. (2006). Jäggi et al. (2006) showed that the dynamic orbit of CHAMP was properly determined using 240 PCA parameters at a 6-min resolution per day. The CHAMP dynamic orbit and the estimated PCAs were used to compute the CHAMP-dynamic-related non-gravitational forces that were consistent with the
measurements of the STAR accelerometer onboard CHAMP. Jäggi et al. (2006) also suggest that the daily non-gravitational forces of CHAMP can be adequately modeled using 240-PCA parameters. The impact of orbit improvement by PCAs is especially pronounced at the frequency of once-per-revolution. As such, a low-altitude LEO like GRACE can benefit greatly from the use of PCAs in precisely modeling the effects of the non-gravitational forces in orbit dynamics.

We designed two dynamic orbits derived from different parameterized PCAs per day for the geocenter motion estimation: 15 PCAs (96-min resolution for the non-gravitational forces) and 240 PCAs (6-min resolution). Use of 15 PCAs is due to the fact that the two GRACE satellites revolve around the Earth 15 times a day. We set up each PCA per cycle revolution in the radial, along-track and cross-track directions to model the non-gravitational forces. The reason for using 240 PCAs is mainly to adequately model the non-gravitational forces acting on GRACE and to conform to the force models used for GOCE DOD (Bock et al., 2011).

3. Eight years of geocenter measurements from orbit differences

3.1. Impact of different non-gravitational models on geocenter measurements

In the following, we separately compare two reduced-dynamic orbits with the kinematic orbit and present a time series of the orbit differences from 2005 to 2012. Generally, the orbit differences in \((r_{\text{kin}} - r_{\text{dyn}})\) show the quality of orbit. However, in our proposed method, the orbit difference can serve as the geocenter measurement and is the result of the relative motion between CN and CM, allowing us to estimate the geocenter motion. As such, \((r_{\text{kin}} - r_{\text{dyn}})\) is a vector of “geometry minus motion”, and is used to estimate the translations from the CN- to the CM-based systems. Here, we compare the CM-based dynamic orbit with the CN-based kinematic orbit to assess the quality of geocenter measurement over 2005–2012.

If the uncertainties in determining \(r_{\text{kin}}\) are minimized, the key factor affecting the quality of geocenter measurement is the accuracy of \(r_{\text{dyn}}\), which is mainly governed by non-gravitational forces. Fig. 2 shows the RMS time series of daily geocenter measurement from 2005 to 2012 using GRACE GPS data. Overall, the RMS values of geocenter measurements from the 240-PCA setup are relatively small compared to those from the 15-PCA setup. This suggests that the 240-PCA setup outperforms the 15-PCA setup in absorbing the orbit perturbing forces. Compared to the 15-PCA orbit, the 240-PCA orbit is more consistent with the kinematic orbit, implying that the consistency between the reduced-dynamic orbit and the kinematic orbit increases with the number of PCAs.

Table 2 shows the mean RMS values of the geocenter measurements derived from the 15- and 240-PCA dynamic orbits over 2005–2012. The RMS values of geocenter measurements in all components from GRACE-A are smaller than those from GRACE-B by less than one mm for both the 15-PCA and the 240-PCA cases. Additionally, the RMS value of geocenter measurement in each component is approximately 3.5 cm in the 15-PCA case for both GRACE satellites, and approximately 2 cm in the 240-PCA case. According to Table 2, the quality of the reduced-dynamic orbits is mainly governed by the different
PCA setups (15 vs. 240 PCAs), which cause on average 1.5 cm orbit differences that will affect the estimation of the geocenter motion.

### 3.2. Impact of F10.7 on geocenter measurement

Fig. 2 shows a dramatic increase of the geocenter measurements after 2011 in the 15-PCA case. This increase is not observed in the 240-PCA case. This is because the former cannot adequately model the atmospheric density variations associated with the F10.7 increase. The blue- and black-shaded segments in Fig. 2 show the time spans with anomalous atmospheric densities over 2005–2012. Such anomalies are most likely caused by an anomalously large geomagnetic index $K_p$ and solar flux index F10.7 (Montenbruck and Gill, 2011). The $K_p$ index is effective mostly for an atmospheric density below 200 km (McCarthy, 1993). The GRACE orbit is approximately 450 km above the Earth’s surface, and therefore F10.7 is the major factor affecting atmospheric density, and in turn also geocenter measurement.

The F10.7 index is an indicator of the solar activity associated with radio emission measurements from the Sun at a 10.7 cm wavelength, and it is highly correlated with the number of sunspots. We filtered the daily F10.7 records (ftp://ftp.ngdc.noaa.gov/STP/GEOMAGNETIC_DATA/INDICES/KP_AP/) with a 100-day moving average and then compared the results with the RMS values of geocenter measurements. Figs. 3 and 4 show the correlation coefficients between the F10.7 index and the RMS values of geocenter measurements in the 15-PCA and 240-PCA cases, respectively. In the 15-PCA case (Fig. 3), the RMS values of geocenter measurements in all components are below 4 cm when the F10.7 index is smaller than 100; the RMS values of geocenter measurements increase when the F10.7 index exceeds 100. In contrast, the RMS values of geocenter measurements in the 240-PCA case (Fig. 4) are not affected by F10.7 and are all almost below 4 cm even if F10.7 exceeds 100.

The time span of the GRACE mission (2002-present) overlaps with that of the 23rd (1997–2008) and the 24th solar cycles (2009–2020). Fig. 5 shows the variation of F10.7, with the lowest value occurring in 2008–2009. From 2005 to 2011, F10.7 was relatively small, and this leads to equally small RMS values of geocenter measurements in both 15- and 240-PCA cases (see Fig. 2). However, the RMS values of geocenter measurements in Fig. 2 increased since 2011 in the 15-PCA case when the F10.7 index exceeds 100. Thus, in the 15-PCA case, the geocenter measurements are susceptible to the F10.7 anomalies in the 24th solar cycle.

Table 3 shows the correlation coefficients between the RMS values of geocenter measurements and the F10.7 over 2005–2012. The correlation patterns in GRACE-A and GRACE-B satellites are consistent not only in the 15-PCA case but also in the 240-PCA case. In the 15-PCA case, the correlation ranges from 0.84 to 0.90, whereas in the 240-PCA case, the correlations are much lower at approximately $-0.10$ to $0.00$. From Table 3, we conclude

### Table 2

The mean RMS of geocenter measurement (in cm) derived from 15 and 240 PCAs from 2005 to 2012.

<table>
<thead>
<tr>
<th></th>
<th>GRACE-A</th>
<th>GRACE-B</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>X</td>
<td>Y</td>
</tr>
<tr>
<td>15 PCAs</td>
<td>3.46</td>
<td>3.39</td>
</tr>
<tr>
<td>240 PCAs</td>
<td>1.93</td>
<td>1.88</td>
</tr>
</tbody>
</table>
that the non-gravitational orbit perturbations, including the F10.7 impact, can adequately be modeled by 240 PCAs, not by 15 PCAs.

4. Geocenter motion estimated from 8 years of GRACE orbit differences

4.1. Effect of PCA on the estimated annual geocenter motion

As shown in Fig. 2, the geocenter measurement is highly correlated with the F10.7 variation in the 15-PCA setup but is not sensitive to such F10.7 variations in the 240-PCA setup. Therefore, we assess the PCA effect on the geocenter motion by comparing the 15-PCA solution with the 240-PCA solution.

According to Eq. (2), we daily generated 8640 orbit differences to compute daily translation parameters (geocentric position). Subsequently, we used a median filter to obtain a monthly geocenter solution in order to remove outliers. Fig. 6 shows the geocenter motions derived from 15- and 240-PCA setups. For both the 15- and 240-PCA setups, the solutions using GRACE-A and GRACE-B GPS data are consistent to sub mm. Because the two GRACE satellites yield consistent solutions, only the combination solution using both satellites is presented in the following development.

As indicated in Fig. 6, the amplitudes of the annual signal from the 15-PCA setup in all components are significantly larger than those from the 240-PCA setup. This implies that the non-gravitational and gravitational orbit

Fig. 4. The correlation coefficient between the RMS of the 240-PCA geocenter measurement and the F10.7 index for (a) GRACE-A and (b) GRACE-B.

Fig. 5. The variation of the F10.7 index over the period of the 23rd and 24th solar cycles.
perturbations (including the geocenter motion) can be absorbed by PCA estimates when increasing the number of PCA parameters more and more in DOD. To show the difference in the frequency domain, Fig. 7 shows the amplitude spectra of the combination solutions using the 15-PCA and 240-PCA setups. Based on Figs. 6 and 7, the annual variations in the X and Y components are much more evident in the 15-PCA case than in the 240-PCA case. However, the time series of the Z component from the 15-PCA setup is contaminated by a period of 426 days, i.e., close to the Chandler period. The reason of this peak is possibly related to the fact that the ocean pole tide is not completely modeled in the official Bernese 5.2 version, which results in spurious variations in some parameters with a period close to the Chandler wobble. In the official Bernese GNSS Software v.5.2, the ocean pole tide is only modeled with $S_{21}$ and $C_{21}$ terms as recommended by the IERS 2010 Conventions (http://www.bernese.unibe.ch/docs/DOCU52.pdf, p.117). Other terms like $C_{10}$, $C_{11}$ and $S_{11}$ with a period close to 433 days are not modeled and are thus propagated to our geocenter solution.

In addition, the spectra show a 341.3-day periodical variation (tips on Fig. 7), which is closest to the GPS draconitic year (about 351.4 days), in the both geocenter solutions. However, for a short time span (2005–2012), it is not possible to fully separate the draconitic error from the annual signal. Thus, a longer time series is indispensable to assess the full impact of the draconitic periods on kinematic and reduced-dynamic GRACE orbits.

The GPS draconitic year is a repetition period of the GPS satellite constellation with respect to the Sun and such a period yields a periodic systematic error existing in GPS-derived products e.g., in time series of Z-geocenter estimates (Rodriguez-Solano et al., 2014). In Fig. 7 (right), the 341.3-day periodical variation has the largest amplitude in the Z-geocenter. This is due to the fact that the kinematic and 240-PCA orbits are highly dominated by the GPS-related products and the both orbits are very close. Therefore, the GPS draconitic error cannot be removed in the 240-PCA geocenter solution. In comparison (Fig. 7 (left)), the 341.3-day periodical variation is insignificant in the 15-PCA Z-geocenter. The reasons are that (1) the 15-PCA geocenter solution is less affected by the GPS draconitic error than the 240-PCA solution and (2) the signal of the geocenter motion is stronger than the GPS draconitic year.

Table 3
Correlation coefficients between the geocenter measurement RMS and F10.7 index.

<table>
<thead>
<tr>
<th></th>
<th>GRACE-A</th>
<th>GRACE-B</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>15 PCAs</td>
<td>240 PCAs</td>
</tr>
<tr>
<td>X</td>
<td>0.84</td>
<td>-0.07</td>
</tr>
<tr>
<td>Y</td>
<td>0.86</td>
<td>-0.04</td>
</tr>
<tr>
<td>Z</td>
<td>-0.91</td>
<td>-0.06</td>
</tr>
</tbody>
</table>

The coefficient shows the correlation between F10.7 values and the 15-PCA geocenter measurement.

![Fig. 6](image-url) (Left) The 15-PCA geocenter motion and (right) the 240-PCA geocenter motion: the GRACE-A solution (blue), the GRACE-B solution (green) and the combined solution (A + B) (red). The time series of the combined solution (A + B) is fitted by a linear equation with a harmonic term (black): $dy(t) = a + bt + K \cdot \cos(2\pi \cdot f \cdot (t - t_0) - \phi)$, where $dy$ is one of the three components of the geocenter, $K$ and $\phi$ are the amplitude and initial phase, respectively; $f$ is the frequency in cycle per year and $t$ is the actual time of the data set; $t_0$ usually denotes January 1 of a particular year; and $a$ and $b$ denote the bias and trend of the geocenter motion, respectively.
The time series of the geocenter motion is fitted by a linear equation with the annual terms (see the figure caption of Fig. 6). Table 4 lists the amplitudes and phases of the geocenter motions from the 15-PCA and 240-PCA cases. Overall, the amplitudes of the annual variations in the 15-PCA solution are larger than those in the 240-PCA solution by 3.2, 1.4 and 1.1 mm in the X, Y and Z components, respectively. In addition, the formal errors derived from the 15-PCA solution are relatively large compared to those derived from the 240-PCA solutions. This is related to a limited capability of the absorption of non-gravitation orbit perturbations by 15-PCA setup, which is strongly subject to the atmospheric density variations indexed by F10.7 (see Fig. 2). The phases of the annual variations from the 15- and 240-PCA solutions are consistent to a few degrees, except that there is a 90° difference in the annual X-phases (see Table 4).

4.2. Comparison of new geocenter motion solutions with results from SLR, GPS, inverse method and prediction models

To validate the geocenter motion derived by our method, we compared our results with those derived using GPS data, the inverse method (INV), SLR, and physical prediction models (CLM) (Table 5). The starting date for phase assessments is January 1 of a particular year in all cases.

All geocenter motion solutions in Table 5 use observations from ground stations, except for the GRACE solution described in this paper. Since the 15-PCA geocenter solution during the period of 2011–2013 might be spurious due to the stronger F10.7, we exclude the period in Table 5, only considering the geocenter solution during the period of 2005–2011. Obviously, the amplitudes in the 15-PCA solution over 2005–2011 are reduced as compared to those over 2005–2013. Furthermore, the corresponding X-phase is also reduced from 114° to 95°. The 15-PCA solution is relatively consistent with those given by SLR, GPS, CLM and INV.

As for the 240-PCA solution, the geocenter-phase is consistent with other solutions, but this is not the case for the amplitudes. The geocenter-amplitudes derived from 240 PCAs are underestimated and smaller than those from the fiducial solutions from SLR, INV, GPS and CLM by a few mm. Such few-mm inconsistencies in amplitude (especially for the X and Z components) are caused by the fact that a large number of PCAs also absorbs the geocenter-motion perturbation. Only the Y-amplitude is consistent with the fiducial results given by SLR, INV and CLM.

Table 4
Annual amplitude (in mm) and phase (in degree) of the geocenter motion derived by the 15- and 240-PCAs.

<table>
<thead>
<tr>
<th>Solution</th>
<th>X</th>
<th>Y</th>
<th>Z</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Amplitude</td>
<td>Phase</td>
<td>Amplitude</td>
</tr>
<tr>
<td>GRACE-A (15 PCAs)</td>
<td>4.2 ± 0.5</td>
<td>110 ± 24</td>
<td>3.6 ± 0.4</td>
</tr>
<tr>
<td>GRACE-B (15 PCAs)</td>
<td>4.0 ± 0.5</td>
<td>119 ± 23</td>
<td>3.1 ± 0.4</td>
</tr>
<tr>
<td>GRACE(A + B) (15 PCAs)</td>
<td>4.1 ± 0.5</td>
<td>114 ± 22</td>
<td>3.4 ± 0.4</td>
</tr>
<tr>
<td>GRACE-A (240 PCAs)</td>
<td>0.9 ± 0.2</td>
<td>26 ± 16</td>
<td>2.2 ± 0.1</td>
</tr>
<tr>
<td>GRACE-B (240 PCAs)</td>
<td>0.9 ± 0.2</td>
<td>27 ± 18</td>
<td>1.9 ± 0.2</td>
</tr>
<tr>
<td>GRACE(A + B) (240 PCAs)</td>
<td>0.9 ± 0.1</td>
<td>26 ± 16</td>
<td>2.0 ± 0.1</td>
</tr>
</tbody>
</table>

Fig. 7. The spectra of the geocenter motion in the 15-PCA (left) and 240-PCA (right) cases.
Consequently, our geocenter-phase solution mostly agrees well with other solutions in Table 5. However, the geocenter-amplitudes from 240-PCA solution are a few mm smaller than those from other solutions. This cause is addressed subsequently.

Following Meindl et al. (2013), the perturbing accelerations due to the Z-geocenter shift can be decomposed into the radial ($R$), along-track ($S$), cross-track ($W$) components:

$$\begin{bmatrix} R \\ S \\ W \end{bmatrix} = \frac{1}{\sqrt{3}} \frac{GM}{r} \begin{bmatrix} Z \\ \sin i \sin u \\ \sin i \cos u \\ \cos i \end{bmatrix},$$

where $u$ is the satellite’s argument of latitude. For GRACE satellites orbiting in near-polar orbits $\sin i \approx 1$ and $\cos i \approx 0$, thus, the $Z$-geocenter shift introduces once-per-revolution variations in the both along-track and radial directions with almost maximal variations. On the other hand, there are no cross-track periodic variations caused by the $Z$-geocenter shift. This implies that the estimation of empirical orbit parameters (like PCA) in the radial or along-track directions more frequently than once-per-revolution may result in the absorption of the geocenter shift. Thus, a full geocenter signal can only be recovered by a solution with a number of PCA limited to about 15 parameters per day.

In addition, Table 5 shows that the $Z$-phase of Kang et al. (2009) is inconsistent with the other solutions. Kang et al. (2009) estimated the geocentric position with GPS-related and receiver-related parameters while performing orbit determination. In that paper, the authors used the fiducial GPS stations so that their geocenter-amplitude was consistent with other solutions. However, the method of Kang et al. (2009) may suffer from a high correlation between geocentric positions and GPS-related and receiver-related parameters, such as the GPS orbit/clock, receiver coordinates/clock and troposphere delay. This correlation might be the reason leading to the inconsistencies in the $Z$-phase between the solution of Kang et al. (2009) and others shown in Table 5. By contrast, our solution de-correlates the geocentric position with those GPS-related and receiver-related parameters.

As a final remark, the number of PCA parameters estimated in DOD shall be a trade-off between the quality of the orbit solution and the capability of the geophysical signal recovery, such as the geocenter motion. In Table 5, only the 15-PCA solution is consistent with other solutions given by different space-geodetic techniques, despite a large sensitivity to F10.7-related perturbations. Thus, a small number of PCA parameters is recommended for the geocenter motion estimation in this study.

## 5. Summary and conclusions

In this paper, geocenter motion was estimated using coordinate origin transformation between the kinematic and reduced-dynamic orbits, i.e., “geometry minus motion”. The kinematic orbit is derived from the geometry approach, which is based on the GPS-based reference frame with the origin being CN. The reduced-dynamic orbit results from the solution of the equations of satellite motion, assuming that the orbit origin is the CM. In this study, each of two GRACE satellites is regarded as a probe to measure the geocenter motion. The difference between these two orbits causes the translational vector (geocentric position) from the Helmert transformation.

However, our proposed method has the limitations and challenges that the dynamic property of the reduced-dynamic orbit is highly dominated by the number of the empirical parameters (e.g., PCA) used in orbit determination. The empirical parameters are nominally used to absorb the non-gravitational forces. However, the result from our experiments shows that too many empirical parameters may absorb not only non-gravitational perturbations (including F10.7-related perturbations), but also some gravitational orbit perturbations, like the geocenter motion effect (Eq. (7)).
In addition, the quality of reduced-dynamic orbit still suffers from the imperfect force models. With ever-increasing accuracies in modeling satellite perturbing forces (e.g., Xu, 2008) and in determining satellite kinematic orbit, differences between the dynamic and kinematic orbits will truly reflect geocenter motions that can be efficiently estimated by the proposed method in this paper.

The annual amplitudes in the 15-PCA solution over 2005–2011 are larger than those in the 240-PCA solution by 2.2, 1.1 and 1.2 mm in the X, Y and Z components, respectively. This implies the absorption of the gravitational orbit perturbations (like the geocenter motion) by overusing PCA parameters, whereas the gravitational signals are kept in the 15-PCA solution. The 15-PCA solution is closer to the geocenter motion derived from other space-geodetic techniques, compared to the 240-PCA solution. This suggests that setting up too many PCA parameters in DOD may result in spurious estimations of the geocenter motion. Thus, a small number of PCA estimations is recommended for the determination of geocenter motion using the proposed method.

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