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Analysis on motion of Earth's center of mass observed with CHAMP mission

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Geocenter motion (GCM) is one important topic for constructing and maintaining the terrestrial reference frame and its applications. GCM is studied from CHAMP with the multi-step approach in this paper. Geometric orbits of CHAMP in 2001—2006 are precisely determined with the kinematic method only from the satellite-borne GPS zero-difference data. Then a GCM time series is estimated from the precise kinematic orbits based on the theory of satellite dynamics to fit the CHAMP's real geometric orbits. We compare the series with the geocenter series used in ITRF2005. Then the GCM series are analyzed with Fourier transform and wavelet transformation. The mean motions within 6 years in *TX*, *TY* and *TZ* directions are respectively 0.8 mm, 2.2 mm, and 7.9 mm. The trends of GCM in the three directions are 0.495 mm/a, –0.004 mm/a, and 1.309 mm/a, respectively. The long-term movement (2001—2006) indicates that the crustal figure is changing. The seasonal variations are the main component which may be excited by the mass redistribution of Earth's fluid layer, e.g. ocean, atmosphere and continental water. The inter-annual variations are also found in the GCM series measured with CHAMP.

geocenter motion, CHAMP, power spectral analysis, wavelet transformation

The Earth's center of mass (CM) is the center of total Earth's mass, including the solid Earth and fluid layer, such as atmosphere, oceans and continental water. So CM is not identical to the mass center of solid Earth (CE), and there exists a translation between them, which is called the geocenter motion (GCM)[1,2]. The origin of the terrestrial reference frame (TRF) is defined as CM at a special epoch[3]. TRF is realized and maintained with the space geodetic techniques[4]. CM is the natural center in the satellite dynamics. Therefore, GCM is not only a basic issue for the space

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geodesy, geophysics and space science, but also an important topic to build and maintain the international terrestrial reference frame (ITRF).

GCM is the response to the change of Earth's mass distribution. It is mainly excitated by the temporal variations of mass distribution in the fluid layer of the Earth. So some geophysical variations in the Earth system are observed and modeled to show GCM[5,6]. Based on the satellite dynamics, the coordinates of stations fixed on the crust are solved from the satellite tracking observations to realize TRF, whose origin is CM at the observing epoch. So GCM is determined from the satellite tracking observations of these stations. Therefore, the time series, w.r.t. (with respect to) a conventional origin measured with the space geodetic techniques, such as the Satellite Laser Ranging (SLR), the Global Positioning System (GPS), and the Doppler Orbitography and Radiopositioning Integrated by Satellite (DORIS), is also used to determine GCM[7,8].

There are two methods commonly used to explore GCM from the space geodetic observations[9]. One method is that the degree 1 spherical harmonic expansion of the Earth gravity field is estimated at the observing epoch while fixing a TRF. The other method is that the time series of stations' coordinates are solved with the free-network method while fixing one Earth gravity field model. These stations are used to construct a TRF at the observing epoch. In this way, a TRF series w.r.t. a fixed TRF is obtained.

A campaign of analysis on GCM was sponsored by the International Earth Rotation and Reference System Service (IERS) in 1997—1998[10]. GCM in *TX*, *TY* and *TZ* directions detected by the space geodetic techniques is up to the millimeter level. But the seasonal and secular variations of GCM explored with the space geodetic observations are submerged in errors after the diurnal and semi-diurnal tidal corrections are made with the tidal model, which indicates that GCM is small and the precisions for the space geodetic observations require further improvement. Meanwhile, GCM derived from the geophysical data is obviously dependent on the geophysical models, and not all frequencies appear in the geophysically-derived GCM series, indicating that the higher accuracies of observations and models of the fluid layer are needed.

GCM has been ever studied using the space geodetic and geophysical data, e.g. Eanes et al. with SLR data[11], Dong et al. with 1993—2002 GPS data[5,6], Chen et al. with 1991—1997 SLR data[2], Bouillé et al. and Crétaux et al. with 1993—1998 DORIS data and SLR data[7,12], Wu et al. with 1983—1994 SLR data[13]. The geophysically-derived GCM predictions were mostly intercompared and the geodetic data were used as the external evidence in these studies. The geodetic GCM is consistent with the geophysical GCM in the seasonal band. These studies show that the seasonal GCM may owe to the mass redistribution of the fluid layer, such as atmosphere, oceans and continental water. SLR's GCM best matches the geophysical expectation in both amplitude and phase for the annual component, and DORIS's results are close to SLR's ones except for the amplitude in *TY* direction. The seasonal GCM derived from GPS is close to SLR's one in the equatorial plane except for the amplitude and phase in *TZ* direction.

CHAMP (CHAllenging Minisatellite Payload) is a small satellite mission for geoscientific and atmospheric research and applications, managed by GeoForschungsZentrum Potsdam (GFZ), Germany. One of primary targets of CHAMP is to precisely determine the static Earth gravity field and its temporal variations. Several gravity models from the high-low satellite-to-satellite tracking data of CHAMP have been recovered by Reigber et al.[14—16]. Beginning with CHAMP, the gravity field model accuracy was improved by a factor of 30[17]. Perturbation of GCM on the satellite orbit cannot be ignored for the precise orbit determination and recovery of Earth gravity field model.

CHAMP flying on a low-altitude orbit was used to detect the temporal variation of low-degree harmonic coefficients of Earth gravity field. Integrated adjustment of CHAMP, GRACE and GPS data was ever made by Zhu et al.[18], who suggested that this integrated adjustment considerably improves the accuracy of the ephemeris for the high and/or low satellites, geocenter variations and gravity field parameters, compared to the case when the adjustment was carried out stepwise or in individual satellite solutions. The integrated solution was adopted to look more closely into the solution of low degree parameters of the spherical harmonic expansion of the gravity field model by König et al.[19]. But a super computer is needed for the integrated adjustment.

For the PC computation, the multi-step approach is adopted to study the GCM with CHAMP mission in this paper. In the first step, orbits and clock corrections of GPS satellites are estimated using GPS ground-based data. In the second step, CHAMP geometric orbits are solved using only satellite-borne GPS data with the kinematic method. In the last step, GCM is studied from the precise kinematic orbits of CHAMP with the dynamical method. The geocenter series is analyzed with the Fourier and wavelet transformation to detect GCM variations.

1 Calculation of GCM from degree 1 harmonic coefficients

In an ITRF fixed on the crust, the position of CM is expressed as

$$\begin{pmatrix} TX \\ TY \\ TZ \end{pmatrix} = \frac{1}{M_e} \iiint_\sigma \boldsymbol{s}\rho(\boldsymbol{s})\mathrm{d}^3\boldsymbol{s}, \tag{1}$$

where M_e is the Earth's total mass, σ is the integrated region which is the whole Earth, and $\rho(\boldsymbol{s})$ is the density at position s in the Earth.

GCM can be expressed as a time series of degree 1 harmonic coefficients in the Earth's gravity field model, and GCM has a definite time scale. According to the geopotential theory[20], the degree 1 coefficients of gravitational potential are

$$\begin{cases} C_{10} = \dfrac{1}{M_e R} \iiint_\sigma r\sin\phi\rho(\boldsymbol{s})\mathrm{d}^3\boldsymbol{s} = \dfrac{TZ}{R} = \sqrt{3}\overline{C}_{10}, \\ C_{11} = \dfrac{1}{M_e R} \iiint_\sigma r\cos\phi\cos\lambda\rho(\boldsymbol{s})\mathrm{d}^3\boldsymbol{s} = \dfrac{TX}{R} = \sqrt{3}\overline{C}_{11}, \\ S_{11} = \dfrac{1}{M_e R} \iiint_\sigma r\cos\phi\sin\lambda\rho(\boldsymbol{s})\mathrm{d}^3\boldsymbol{s} = \dfrac{TY}{R} = \sqrt{3}\overline{S}_{11}, \end{cases} \tag{2}$$

where r, λ and ϕ are the spherical coordinates at position s in the Earth, C and S are the potential coefficients, $\overline{C}$ and $\overline{S}$ are the fully normalized potential coefficients, and R is the Earth's radius.

If the origin of the coordinate system is CM, then $C_{10} = \overline{C}_{10} = 0$, $C_{11} = \overline{C}_{11} = 0$, and $S_{11} = \overline{S}_{11} = 0$. So $TX = TY = TZ = 0$. Because of the mass redistribution, there is difference between the origin of TRF and CM, which causes $C_{10} \neq 0$, $C_{11} \neq 0$, and $S_{11} \neq 0$. GCM can be expressed as a function of degree 1 harmonic coefficients, that is

$$\begin{cases} TX = RC_{11} = \sqrt{3}R\overline{C}_{11}, \\ TY = RS_{11} = \sqrt{3}R\overline{S}_{11}, \\ TZ = RC_{10} = \sqrt{3}R\overline{C}_{10}. \end{cases} \tag{3}$$

If degree 1 coefficients of gravitational potential are known, GCM can be calculated from eq. (3).

2 Time series of GCM from CHAMP

We will study GCM from CHAMP mission with the multi-step approach. The GPS final orbits and high-rate clock corrections are estimated by the Center for Orbit Determination in Europe (CODE), which are conformably transformed to ITRF2000 at epoch J2000.0.

The geometric orbit of CHAMP firstly is precisely determined with the kinematic method[21] using the satellite-borne GPS zero-difference data, not ground-based data, through 2001 to 2006, with Bernese 5.0 software. The standard deviation for the CHAMP kinematic orbit is 0.031 m compared with the tracking distances by SLR. The accuracy of SLR range is up to the subcentimeter or millimeter level, so this geometric orbit of CHAMP with the kinematic method has the precision up to the subcentimeter level, which can be used to compute the low-degree gravitational potential coefficients.

6-year geometric orbits series of CHAMP in 2001—2006 are divided into many 7-day arcs, which are used to recover the low-degree gravitational model up to 10 degrees including degree 1 coefficients. So there are 4 arcs in one month. Table 1 lists the main standard models and parameters in this calculation.

Table 1 Main standard models

Referenced Earth gravity model	EIGEN-3p	Non-gravitational forces	Observations from CHAMP's accelerometer
Multi-body perturbation	DE200	referenced epoch	J2000.0
Tidal model	EGM96	referenced frame	ITRF2000
Precession and nutation	IAU2000	polar motion and UT1	IERS

In practice, to recover the geopotential model is to smooth the geometric orbit in the least squares sense. Now GCM is calculated from degree 1 potential coefficients by eq. (3), which forms a time series of GCM. Then the GCM series is filtered by the low-pass Gaussian filter whose window size is 60 days and one sample is sampled every month, not weekly. Table 2 gives the statistical results for the GCM series. The average motions in *TX*, *TY*, and *TZ* directions in 2001—2006 are 0.8 mm, 2.2 mm, and 7.9 mm, respectively. In order to evaluate the geocenter series measured with CHAMP, we compare it with the geocenter series used in ITRF2005 which is also filtered with the low-pass Gaussian filter. The geocenter series for ITRF2005 is estimated from the SLR data. The comparison results are shown in Figure 1. Table 3 lists the statistical results, which indicates that the precision in *TZ* direction is more accurate than those in *TX* and *TY* directions.

Seasonal variations are the main part of GCM[2,5]. The seasonal geocenter variations are derived with the least squares method using the following approximation:

$$g(t) = a + b(t - t_0) + A\sin\left[\frac{2\pi}{p}(t - t_0) + \varphi\right], \tag{4}$$

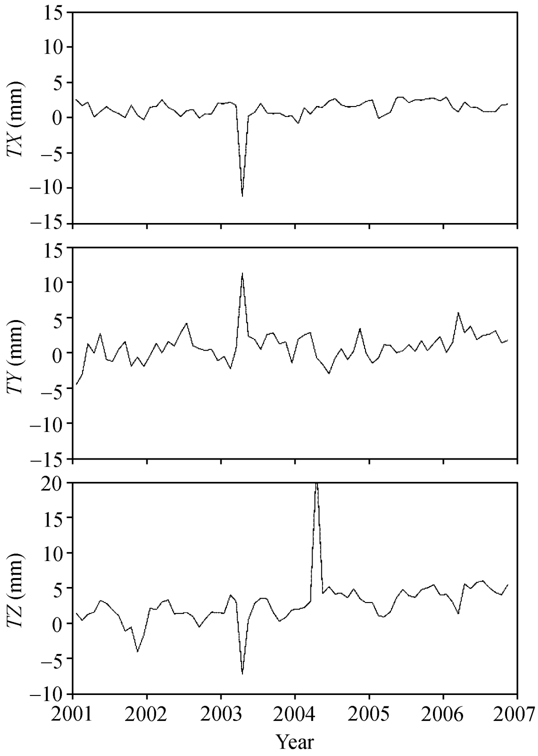

Figure 1 Differences between the geocenter series measured with CHAMP and the series used in ITRF2005.

Table 2 Statistical results of GCM measured with CHAMP

Coordinates	Maximum (mm)	Minimum (mm)	Average (mm)
TX	6.6538	–4.7713	0.8347
TY	10.2256	–6.1655	2.2260
TZ	18.7712	–1.7336	7.9114

Table 3 Comparison of geocenter series with those for ITRF2005

	Maximum (mm)	Minimum (mm)	Mean difference (mm)	Standard deviation (mm)
TX	2.95	–11.14	1.216	1.739
TY	11.34	–4.48	0.955	2.210
TZ	22.74	–7.13	2.848	3.287

where a is the offset, b is the trend rate, t is time, t_0 is the initial time (2001.0), φ is the initial phase, A is the amplitude, and p is the period.

The trends solved in *TX*, *TY*, and *TZ* directions within these 6 years are 0.495 mm/a, –0.004 mm/a, and 1.309 mm/a, respectively. Chavet et al.[22] ever showed that the long terms of GCM are up to 3 mm/a in *TX* and *TY* directions, and 7 mm/a in *TZ* direction. The trend of GCM with SLR data through 1993 to 2004 was solved by Kuzin et al.[23], and the trends in *TX*, *TY* and *TZ* directions are 0.1 mm/a, 0.2 mm/a, and 0.6 mm/a, respectively.

The annual amplitudes of GCM measured with CHAMP are 2.1 mm for *TX*, 3.2 mm for *TY*, and 3.1 mm for *TZ*, respectively. The semiannual amplitudes of GCM measured with CHAMP are 0.6 mm for *TX*, 0.7 mm for *TY*, and 0.9 mm for *TZ*. Table 4 shows the measured and predicted seasonal amplitudes of GCM, which indicates that the seasonal amplitudes measured with CHAMP in 2001—2006 are very consistent with the previous studies[2,5,7,11,22,23].

Table 4 Measured and predicted seasonal amplitudes of GCM

Solutions	Annual (mm)			Semiannual (mm)		
	TX	*TY*	*TZ*	*TX*	*TY*	*TZ*
		measured				
CHAMP (2001—2006) in this paper	2.1	3.2	3.1	0.6	0.7	0.9
SLR[11]	2.2	3.2	2.8			
SLR (Lageos 1/2)[7]	2.1	2.0	3.5			
DORIS (SPOT 2/3+T/P)[7]	2.4	2.1	2.1			
DORIS (T/P)[7]	1.8	5.0	3.0			
SLR[22]	1.3	0.9	3.0			
DORIS[22]	1.9	2.8	6.3			
GPS[22]	3.6	3.8	20.0			
SLR (Lageos 1/2, 1993—2000)[23]	3.1	5.5	3.6	1.1	0.8	1.4
SLR (T/P, 1993—2000)[23]	1.8	2.8	2.3	1.5	0.4	3.8
GPS (1993—2004)[23]	3.0	5.0	13.2	14.1	3.3	6.0
		predicted				
Ref. [7]	1.7	2.4	4.6			
Ref. [2]	2.4	2.0	4.1	0.8	0.9	0.5
Ref. [5]	4.2	3.2	3.5	0.8	0.4	1.1

3 Analysis on GCM variations with Fourier and wavelet transform

GCM series measured with CHAMP in 2001—2006 is firstly analyzed with the Fourier transform (FT). A frequency-power chart is composed of the frequency and power in FT, which is used to determine the variations of GCM. So the trend and periodic terms are found, and the contribution for every periodic term is estimated. The power analysis on GCM series measured with CHAMP is shown in Figure 2. There are more powers near frequency zero in all three directions, which indicate that there are obviously secular changes for GCM in *TX*, *TY*, and *TZ* directions through 2001 to 2006. More powers also appear near frequencies 11 and/or 12, which may be derived from the noises and the sampling frequency. The periods detected by FT are listed in Table 5. So there are the long-term and seasonal variations for GCM with FT power analysis.

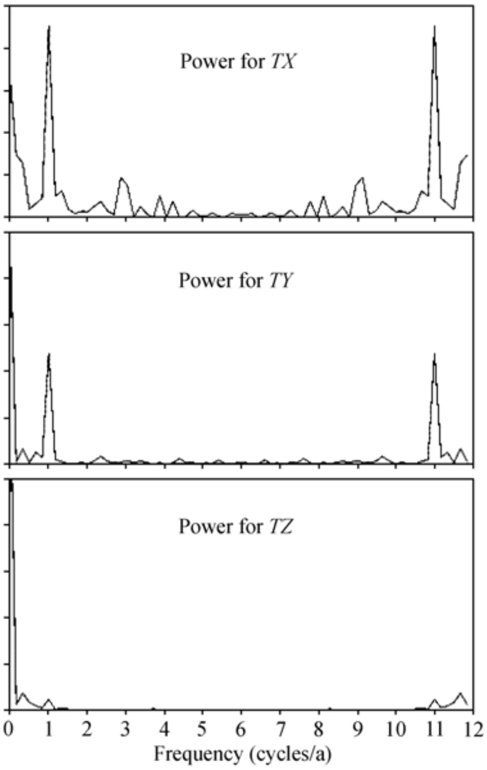

Figure 2 Power analysis on GCM with FT.

The GCM series is also analyzed with the wavelet transform (WT). WT is a signal-analyzed method in time and frequency domains with the variable resolutions, whose mathematical principle is to use a family of functions to approach a signal or a function[24]. Because the Morlet wavelet is a combination of trigonometric and Gaussian functions, it is widely used in the geophysical and geodetic data analysis. Signals are separated from noises in a time series by a wavelet filtering in a time and frequency domain, which efficiently wipes off the effect of noises. Then a clean signal is reconstructed and an ideal function is gotten[25].

The wavelet analysis of GCM series measured with CHAMP is shown in Figures 3—5. The periods detected by WT are listed in Table 5. Figures 3—5 also show that these periods are temporally changing.

Table 5 Periods of GCM variations detected by FT and WT

		Periods (d)
TX	FT	1080, 360, 270, 154, 127
	WT	1006, 598, 356, 126
TY	FT	1080, 540, 360, 154, 120
	WT	1006, 356, 178, 150
TZ	FT	1080, 422, 360, 270, 180, 154
	WT	1006, 598, 423, 356, 178, 150

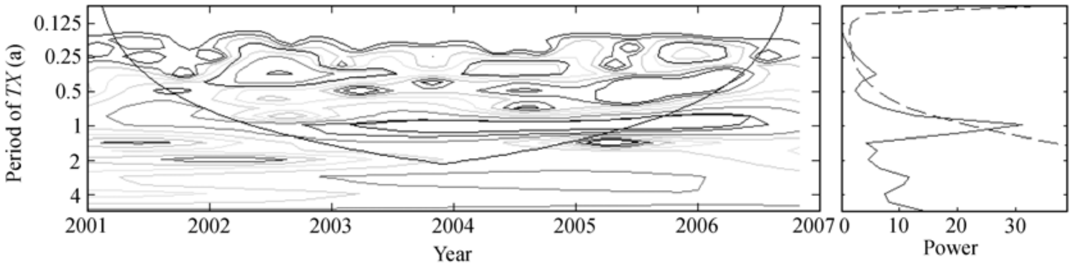

Figure 3 Wavelet analysis for *TX*.

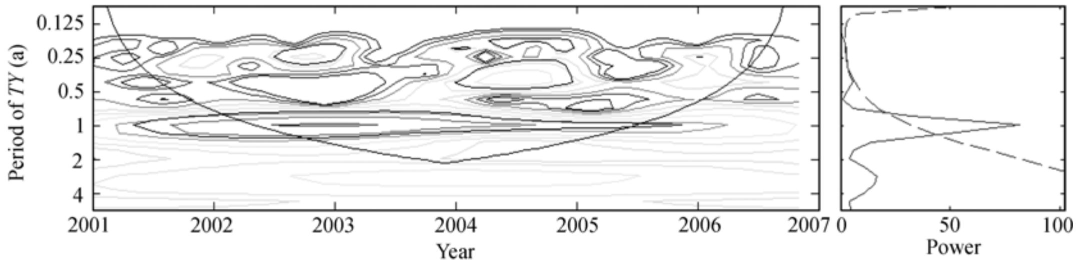

Figure 4 Wavelet analysis for *TY*.

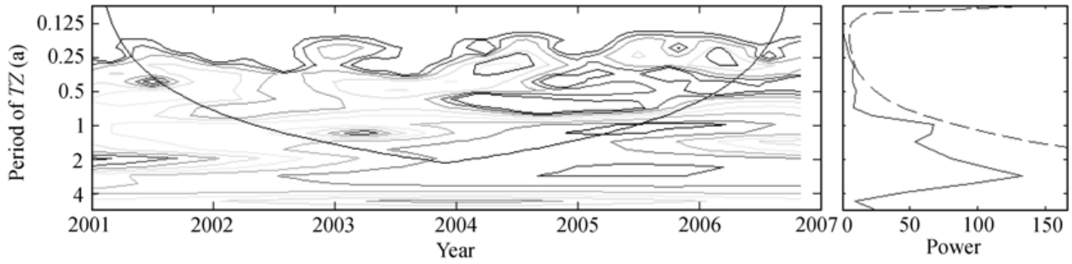

Figure 5 Wavelet analysis for *TZ*.

4 Discussion

GCM measured with CHAMP shows itself the visible secular variation in 2001－2006. The power centralizes near the 0-frequency in the FT analysis, seen in Figure 2. The trend in *TY* direction is –0.004 mm/a, different from the ones in *TX* and *TZ* directions, which are 0.495 mm/a and 1.309 mm/a, respectively. The CHAMP-derived trend basically accords with that from Chavet et al.[22] and Kuzin et al.[23].

The secular change rate in *TZ* direction is the largest and positive. This indicates that the center of Earth's figure (CF) is moving southwardly w.r.t. CM, that is to say, CM could move northwardly relative to CF if CF was fixed.

The seasonal variations that include the biannual and annual fluctuations are the main part in GCM, which may be principally derived from the mass redistribution of atmosphere, ocean and continental water[2,5,9,10,26,27]. Seasonal variations are obviously all shown in the FT and wavelet analysis in the paper.

The FT analysis shows that there are the annual and semiannual variations in *TX*, *TY* and *TZ* directions. The annual period is 360 days. But the semiannual period temporarily changes through 5 to 7 mon in *TX* and *TY* directions. There is the semiannual variation in *TZ* direction, but the period is also variable. A number of encouraging studies only show that there are seasonal variations of GCM, but the idiographic periods are not given, e.g. Dong et al.[5], Chen et al.[2], Wu et al.[13], Bouillé et al.[7], Crétaux et al.[12], and Feissel-Vernier[9].

There are obvious seasonal variations in *TX*, *TY* and *TZ* directions explored by the WT analysis. But the semiannual and annual periods have a small fluctuation with 1 to 2 mon. The annual variations in three directions are all found, but the period is 356 days, which is different from 360 days detected by FT. Especially the semiannual variation in *TX* direction is not evident. Speaking in this way, seasonal variations in *TX*, *TY* and *TZ* directions are all shown in the FT and WT analysis.

The least square analysis shows that the annual amplitude is larger than the biannual amplitude, e.g. 2.1 mm vs. 0.6 mm in *TX*, 3.2 mm vs. 0.7 mm in *TY*, and 3.1 mm vs. 0.9 mm in *TZ*. The seasonal amplitudes of GCM measured with CHAMP in *TX*, *TY* and *TZ* directions are of the consistent amplitude, which well accord with the previous studies, e.g. Eanes et al.[11], Chen et al.[2], Bouillé et al.[7], Dong et al.[6], Chavet et al.[22], and Kuzin et al.[23].

The peak value of seasonal variations of GCM in *TX* direction takes place in July to September, and the trough value appears in January to March. The peak value of seasonal variations in *TY* direction is present in June to August, and the trough value takes place in December to February of the next year. The peak value of seasonal variations appears in May to July, and the trough value takes place in November to January of the next year.

The seasonal GCM may be mainly caused from the mass redistribution of Earth surface fluid layer. The variation in the equatorial plane may be excitated by the ocean, atmosphere, and in part continental water. The atmosphere acts on the ocean with the inverse-barometer effect so that it is difficult to partition the effect of atmosphere and/or ocean. The largest variation of atmospheric pressure appears in the middle Asia, which is a seasonal change[27]. This makes CM vibrate in *TY* direction. There are another two largest variations of atmospheric pressure that take place in the north Pacific and the north Atlantic, respectively, which make CM vibrate in *TX* direction. The seasonal motion in *TZ* direction may be derived from the continental water exception for in part the atmosphere and ocean. Feissel-Vernier et al.[9] ever analyzed the spectral signal of Earth's surface fluid with the Allen's variance method. There are obvious annual fluctuations for the continental waters in *TX*, *TY* and *TZ* directions, and there are seasonal and non-seasonal variations in the oceanic and atmospheric spectrums. The excitation of atmosphere and ocean is of white noise in the equatorial plane, and that in *TZ* direction is of flicker noise. Therefore, the trend of GCM measured with CHAMP may be mainly caused from the atmosphere and ocean, which is relative to the global warm and the melt of glacier.

A period of 1080 days is found in the FT analysis, which basically accords with that period of 1006 days detected by the WT analysis. WT found a period of 598 days in *TX* and *TZ* directions, not in *TY*. FT only found a period of 540 days in *TY* direction, not in the other directions. These periods are called inter-annual period. Lambeck[27] ever showed that there is a period of 545 days for the polar tide of atmosphere, which is very close to 540 days given in the paper. So this periodic variation of GCM may be excitated by the polar tide of atmosphere. In practice, because there are only 6-year data, these periodic variations may be not reliable.

A period of 422 days in *TZ* is found in the FT analysis, which is basically the same as the period of 426 days by the WT analysis. But this period in the equatorial plane is not found. The period is calculated from the frequency with the maximum power. So the core and mantle may be likely to wobble a little in the axis rotating direction, and the wobble does not appear in the equatorial plane or it is too small to be found. By the way, the frequency is very close to that of Chandler wobble.

5 Conclusions

The secular and periodic variations of GCM measured with CHAMP in 2001—2006 are calculated with the multi-step approach and detected with the FT and WT analysis, respectively. The trend movement of GCM indicates that the crustal geometric figure is changing in the inertial space. This may be derived from the glacial rebound, sea level rising, global warming, human activities and so on.

The seasonal variations are the main component which may be caused by the mass redistribution of Earth fluid layer, e.g. ocean, atmosphere and continental water. There are many other periodic or quasi-periodic variations. The 422-day fluctuation in *TZ* possibly reveals that the core and mantle may wobble a little in the rotating direction and it is not obvious in the equatorial plane, which is close to that of Chandler wobble. The 540-day variation in *TZ* may be excitated by the polar tide of atmosphere. Many periods gradually change, which are called quasi periods. This indicates that there exist nonregular fluxes for the environment and mass of the whole Earth system.

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