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A study of gravity variations caused by polar motion using superconducting gravimeter data from the GGP network

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Abstract. Long-term continuous gravity observations, recorded at five superconducting gravimeter (SG) stations in the Global Geodynamic Project (GGP) network, as well as data on orientation variations in the Earth's rotation axis (i.e. polar motion), have been used to investigate the characteristics of gravity variations on the Earth's surface caused by polar motion. All the SG gravity data sets were pre-processed using identical techniques to remove the luni-solar gravity tides, the long-term trends of the instrumental drift, and the effects of atmospheric pressure. The analysis indicates that the spectral peaks, related to the Chandler and annual wobbles, were identified in both the power and product spectral density estimates. The magnitude of gravity variations, as well as the gravimetric amplitude factor associated with the Chandler wobble, changed significantly at different SG stations and during different observation periods. However, when all the SG observations at these five sites were combined, the gravimetric parameters of the Chandler wobble were retrieved accurately: 1.1613 ± 0.0737 for the amplitude factor and $-1°.30 \pm 1°.33$ for the phase difference. The value of the estimated amplitude factor is in agreement with that predicted theoretically for the zonal tides of an elastic Earth model.

Key words: Superconducting gravimeter – Global Geodynamic Project – Polar motion – Gravimetric parameters – Chandler wobble

1 Introduction

Similar to the luni-solar tidal forces, the periodic perturbations in the inertial centrifugal force, which come from polar motion and variations in the length of day (LOD), induce long-period deformation and gravitational variations of the Earth (see e.g. Wahr 1985), as well as the oceanic pole tide loading on the Earth's surface (Dickman and Steinberg 1986; Dickman 1988). The oceanic pole tide may also lead to the loading deformation and gravitational perturbations of the Earth. However, it has been found that the pure loading effects of the dynamic pole tide may be neglected in measurements (Wahr 1985). The effect of variations in LOD is about two orders of magnitude less than that of polar motion. Therefore, LOD effects were neglected in our study. Polar motion of the Earth almost entirely consists of the annual wobble (AW) and the Chandler wobble (CW) which has a period of approximately 14 months. In mid-latitude regions, the peak-to-peak magnitude of gravity fluctuations induced by polar motion is as large as 10–13 μGal.

Thanks to the advantages of the high sensitivity, strong stability, relatively low drift, and very wide frequency range of the active linear response, superconducting gravimeters (SGs) play an important role in the detection and studies of global and local geodynamic phenomena. Long-period gravity variations, associated with perturbations of the Earth's rotation and other geodynamic phenomena, have been observed because of the considerable accumulation of superconducting gravimeter (SG) records (Richter and Zürn 1988; De Meyer and Ducarme 1991b; Xu et al. 1998; Loyer et al. 1999; Sato et al. 2001). However, in most previous studies, only SG gravity data obtained at a single site were used, and consequently the results may be contaminated by the relatively large, long-period background perturbations around the station. Therefore, considering the global nature of the polar-motion-induced gravity variations may eliminate the local environment influences and lead to much more accurate results. This is achieved effectively by stacking the long-term SG observations at several sites in different regions (Cummins et al. 1991; Cummins and Wahr 1993; Smylie et al. 1993; Defraigne et al. 1994; Courtier et al. 2000; Xu et al. 2002).

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The Global Geodynamic Project (GGP), launched by the Committee on the Study of the Earth's Deep Interior (SEDI) belonging to the International Union of Geodesy and Geophysics (IUGG), suggests that it is beneficial to studies and detection of many global geophysical and geodynamic phenomena to combine the global SG continuous measurements over a six-year duration from July 1997 to June 2003 (Crossley et al. 1999). One of the main purposes of the GGP is to effectively separate the gravity signals associated with the AW and the CW in the long-term gravity residuals, and to investigate the characteristics of gravity variations induced by polar motion.

The main motivation for the study reported in this paper is to investigate the nature of the gravity variations caused by polar motion of the Earth, by combining the long-term SG gravity observations at five GGP stations, as well as the simultaneous data of the atmospheric pressure and polar motion, COMB2001, provided by Gross (ftp://euler.jpl.nasa.gov/keof/combinations/2002).

2 Gravity variations induced by polar motion

The disturbing inertial force, coming from variations in the Earth's rotation, deforms the Earth as an external body force. Using a first-order approximation of the polar motion, perturbations in the inertial potential may be written as (Wahr 1985)

$$V_1(r,\theta,\lambda) = -\frac{r^2\Omega^2}{2}\sin 2\theta \cdot (m_1\cos\lambda + m_2\sin\lambda) \tag{1}$$

where r is the distance from the geocenter to any reference site on the surface or within the interior of the Earth, θ and λ the co-latitude and eastward longitude, respectively, m_1 and m_2 the dimensionless polar motion, and Ω the mean rate of the Earth's rotation.

Potential perturbations V_1 (r, θ, λ), given by Eq. (1), are similar to the second-degree luni-solar tide-generating potential. For site $S(a, \theta, \lambda)$ on the Earth's surface (a is the radius of the Earth), the gravity fluctuations, caused by polar motion, may be obtained as

$$\Delta g_0(S,t,\delta) = \delta a\Omega^2 \sin 2\theta \cdot [m_1(t)\cos\lambda + m_2(t)\sin\lambda] \tag{2}$$

where $\delta = 1 + h - \frac{3}{2}k$ is the second-degree gravimetric amplitude factor, in which both h and k are the second-degree Love numbers for the body tides. The value of δ is 1 for a rigid Earth, and about 1.16 for a spherical and perfectly elastic Earth (Wahr 1981; Xu and Sun 2003). It is quite convenient to theoretically predict temporal series $\Delta g_0(S,t,\delta)$ of the gravity variations, caused by polar motion, by using the polar motion data.

At present, polar motion (m_1 and m_2) is accurately estimated because of the development of the space-geodetic and astrometric techniques. In this study, we used the daily polar motion data, COMB2001, attained by combining the space-geodetic measurements of lunar and satellite laser ranging, very long baseline interferometry and the global positioning system, and optical astrometric measurements [see Gross (2000) for details].

3 Superconducting gravimeter measurements

The gravity data used in this study are the long-term continuous SG observations recorded at five GGP stations: Brussels and Membach in Belgium, Strasbourg in France, Potsdam in Germany, and Boulder in the USA. Based on the simultaneous station barometric pressure data at each SG site, the effects of atmospheric pressure loading were removed from the raw gravity records. Basic information about the five SG stations used is given in Table 1.

In order to avoid some artificial and unnecessary discrepancies arising from the data treatment, identical techniques of pre-processing and harmonic analysis were employed to analyze all five of the gravity data sets at the International Center of the Earth's Tides (ICET). "T-Soft", a graphical and interactive software for analysis of Earth-tide data, developed by Vauterin (1998), was used to remove some bad records such as spikes, steps and large-amplitude vibrations caused by earthquakes, and to interpolate some small gaps in the 20-s-sampled data by means of man-to-computer dialogue. A high-pass filter was used to transform the 20-s-sampled data series to the hourly ones. The gravimetric parameters (i.e. amplitude factors δ and phase differences $\Delta\varphi$) and the station barometric gravity admittance C were determined for each data set with ETERNA 3.30, which is a standard harmonic analysis software developed by Wenzel (1998). In the harmonic analysis, an accurate tide-generating potential with 1200 harmonic tide waves, developed by Tamura (1987), was used.

Using the resulting gravimetric parameters and the barometric admittance, the tidal and atmospheric gravity signals were subtracted from each raw gravity data set to yield the gravity residual set. For each gravity residual set, the long-term trends of the instrumental drift were simulated by a second-order polynomial $Dr(t) = a_0 + a_1 \cdot t + a_2 \cdot t^2$, in which a_0, a_1 and a_2 are the drift parameters to be determined. The barometric admittance and the drift parameters for each data set are also listed in Table 1.

The gravity residual data series, used in the following analysis, are given as

$$\Delta g_1(S,t) = Obs(S,t) - \sum_k \delta_k \sum_{i=\alpha_k}^{\beta_k} A_i \cos(\omega_i t + \varphi_i + \Delta\varphi_k) - C\cdot Pr(S,t) - \sum_{i=0}^{2} a_i \cdot t^i \tag{3}$$

where $\Delta g_1(S, t)$ is the gravity residual at time t and at site S; $Obs(S, t)$ and $Pr(S, t)$ are the original SG gravity and the station barometric pressure records; δ_k and $\Delta\varphi_k$ are the determined amplitude factor and phase difference of the kth tidal wave group on the diurnal, semi-diurnal and ter-diurnal tidal bands, and they were taken the theoretical values of 1.16 and 0 for the long-period tides; α_k and β_k are the initial and final index of the kth tidal wave group in the tide-generating potential table; and

Table 1. Details of the data sequences used

Station	Observing period	Latitude(°N)	Longitude(°E)	Height(m)	C (μGal .hPa^{-1})	a_0	a_1	a_2
Brussels	1986-11-15-2000-09-20	50.7986	4.3581	100.0	-0.3467 ± 0.0049	826.131	-4.33364×10^{-2}	3.95268×10^{-7}
Boulder	1995-04-12-2001-03-29	40.1308	254.7672	1682.0	-0.3568 ± 0.0174	410.057	1.21226×10^{-1}	-6.78259×10^{-7}
Membach	1995-08-04-2000-05-31	50.6093	6.0066	250.0	-0.3286 ± 0.0059	−106.806	8.68150×10^{-2}	-7.62658×10^{-7}
Potsdam	1992-06-30-1998-10-08	52.3809	13.0682	81.0	-0.3313 ± 0.0042	4.269	1.29067×10^{-1}	-1.25675×10^{-6}
Strasbourg	1987-07-11-1996-06-25	48.6223	7.6840	180.0	-0.3128 ± 0.0099	−75.230	3.76773×10^{-1}	-3.09172×10^{-6}

A_i, ω_i and φ_i are the theoretical amplitude, angular frequency, and initial phase of the *ith* tidal wave, respectively. For the sake of convenient comparison, the temporal changes of SG gravity residuals $\Delta g_1(S,t)$ and gravity variations $\Delta g_0(S,t,1.16)$, induced by polar motion, in which the gravimetric amplitude factor was chosen as $\delta = 1.16$ for an elastic Earth model, are shown in Fig. 1.

4 Analysis and discussion

Before analysis of the observed data sets, the third-order Vondrak low-pass filter (see e.g. Feissel and Lewandowski 1984) with the smoothing factor of 4.5×10^{-8} was employed to filter all the gravity residual sets $\Delta g_1(S,t)$ and polar-motion-induced gravity variations $\Delta g_0(S,t,1)$ predicted theoretically for a rigid Earth. They are also denoted as $\Delta g_1(S,t)$ and $\Delta g_0(S,t,1)$ after filtering. The frequency response of this filter is illustrated in Fig. 2.

4.1 Identification of the polar-motion-induced gravity variations

Using the discrete Fourier transform, we may estimate the spectrum of a given long-term data set in the time domain. However, a suitable window function is usually introduced in order to increase the reliability of the spectral estimation. Taking into consideration the different lengths of the data sets used in this study (Table 1), each data set was separated into several segments of the same length with a 75% overlap in order to guarantee identical frequency resolution on the spectral estimates for all the data sets. For a certain data set, the power spectral density estimates were reached by averaging those of its all segments [see e.g. Smylie et al. (1993) for details].

We assumed that N data sets were available. The estimates of their power spectral density were expressed as $\tilde{P}_i(\omega)$, with $i = 1, 2, ..., N$. The product spectral density estimates of all the data sets may be defined as

$$\tilde{P}_{12...N}(\omega) = \left[\prod_{i=1}^{N} \tilde{P}_i(\omega)\right]^{\frac{1}{N}} \tag{4}$$

to keep the same dimension as the power spectral density estimates. In the spectral analysis, the common length of each data segment was taken as 2178 days, the length of the data set recorded at Boulder. The Parzen window was chosen as the window function. The estimates of the long-period power spectral density (PSD) of the gravity residual sets near or over a six-year duration at stations Brussels, Boulder, Potsdam and Strasbourg are presented in Fig. 3.

From Fig. 3, the polar-motion-induced gravity variations are significantly identified in the long-term SG observations, especially in those at stations Potsdam and Boulder. The predominant energies of the low-frequency

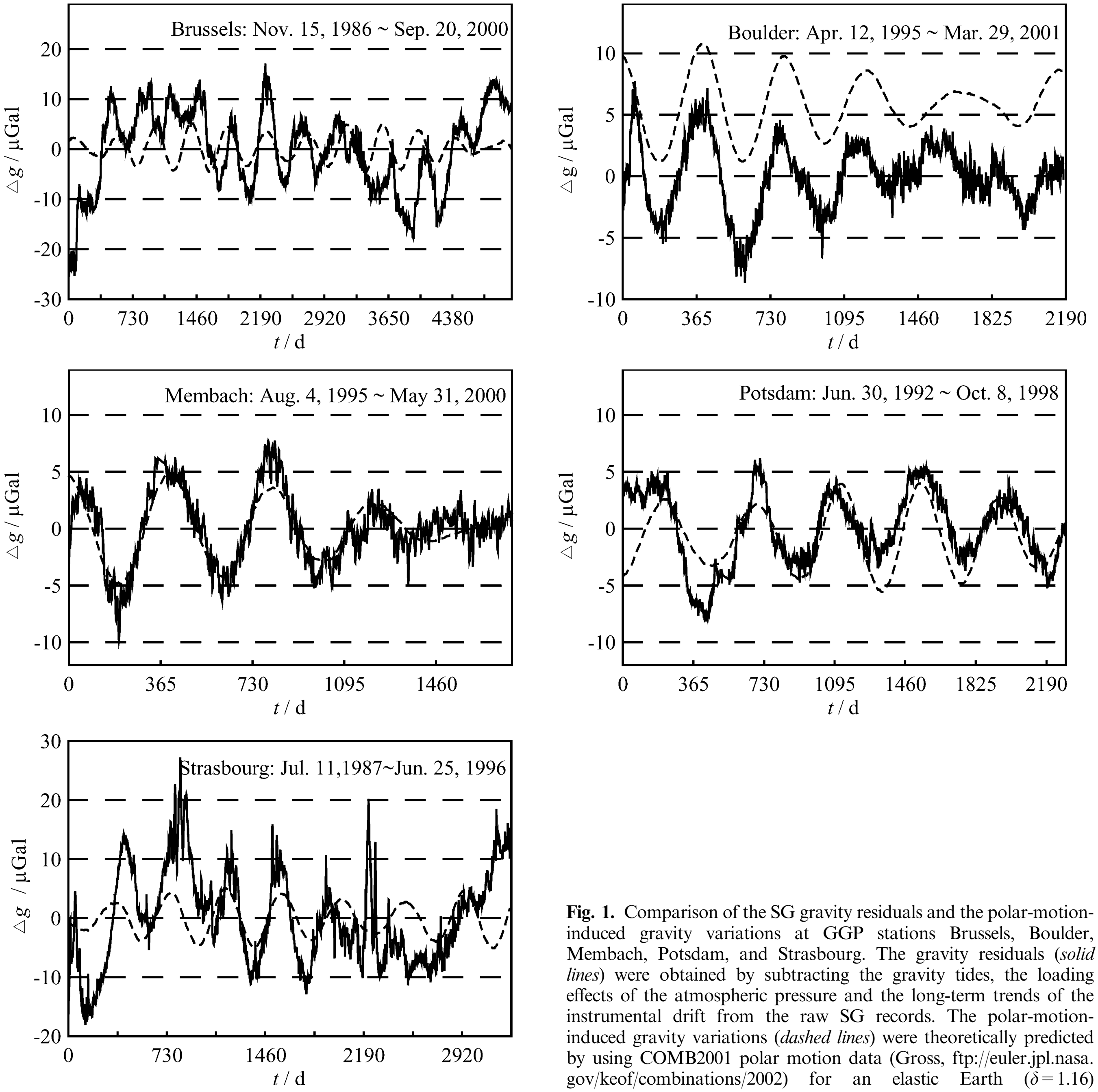

Fig. 1. Comparison of the SG gravity residuals and the polar-motion-induced gravity variations at GGP stations Brussels, Boulder, Membach, Potsdam, and Strasbourg. The gravity residuals (*solid lines*) were obtained by subtracting the gravity tides, the loading effects of the atmospheric pressure and the long-term trends of the instrumental drift from the raw SG records. The polar-motion-induced gravity variations (*dashed lines*) were theoretically predicted by using COMB2001 polar motion data (Gross, ftp://euler.jpl.nasa.gov/keof/combinations/2002) for an elastic Earth ($\delta = 1.16$)

gravity signals, measured at these two SG sites, concentrate mainly on the Chandler and annual periods. Although there exists relatively large low-frequency background noise, the spectral peaks of the Chandler and annual periods are also largest in the PSD estimates of the gravity residuals observed with the SG at Strasbourg. However, there is no obvious energy high near the Chandler or annual period in the PSD estimates of the gravity residuals at Brussels. The gravity signals, associated with polar motion, may be buried in the extremely large environment-related perturbations.

Observed long-period gravity changes come from the combined influences of global and/or local geophysical and geodynamic phenomena, such as long-period variations in the global and/or local atmospheric pressure, sea level, tectonic movement, Earth's rotation, underground and superficial water, and so on. In addition, some systematic errors in the observations, such as offsets appearing in the long-term SG measurements due to instrumental instabilities, may significantly influence the long-term gravity observations. Therefore, the spectral characteristics of the long-period gravity, obtained with the SG at one station, may differ significantly from those at other stations. Stacking measurements from multiple stations in different regions is a desirable way to suppress the influences of the local perturbations around each individual station and some systematic errors in the observations (Cummins et al. 1991; Cummins and Wahr 1993; Smylie et al. 1993; Defraigne et al. 1994; Courtier et al. 2000; Xu et al. 2002). The product spectral density

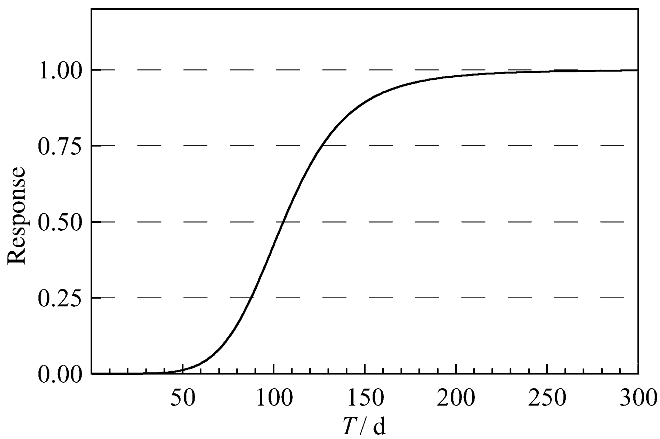

Fig. 2. Frequency response of the third-order Vondrak low-pass filter with the smoothing factor of 4.5×10^{-8}

estimates [Eq.(4)] for these four SG gravity residual sets are illustrated in Fig. 4.

In the product spectral density estimates of the long-term SG gravity residuals observed at stations Brussels, Strasbourg, Potsdam and Boulder (Fig. 3), the energies of the long-period variations mainly concentrate on the Chandler and annual periods; the signals of the other frequencies are relatively weak. The product spectral density estimates of the polar-motion-induced gravity variations are the two spectral lines with the highest energy, which correspond to periods of about 435.6 and 363.0 days.

4.2 Estimates of the gravimetric parameters at the AW and CW periods

From Eq. (2), it is found that the amplitudes of the polar-motion-induced gravity variations depend upon the latitude of a station, while the longitude may only lead to a phase shift. Although preparatory barometric corrections had been implemented in the computation of the gravity residuals $\Delta g_1(S,t)$ (cf. Fig. 1), the mean barometric admittances over the whole frequency range were used in the corrections. Previous studies show that the atmospheric admittance strongly depends upon the signal frequencies and measurement sites (De Meyer and Ducarme 1991a; Merriam 1993; Crossley et al. 1995; Sun and Luo 1998; Xu et al. 1999). Therefore, it was necessary to take further account of the atmospheric effects on the gravity residuals in order to improve the precision of numerical computation. Hence, SG gravity residuals $\Delta g_1(S,t)$ were simply modeled as

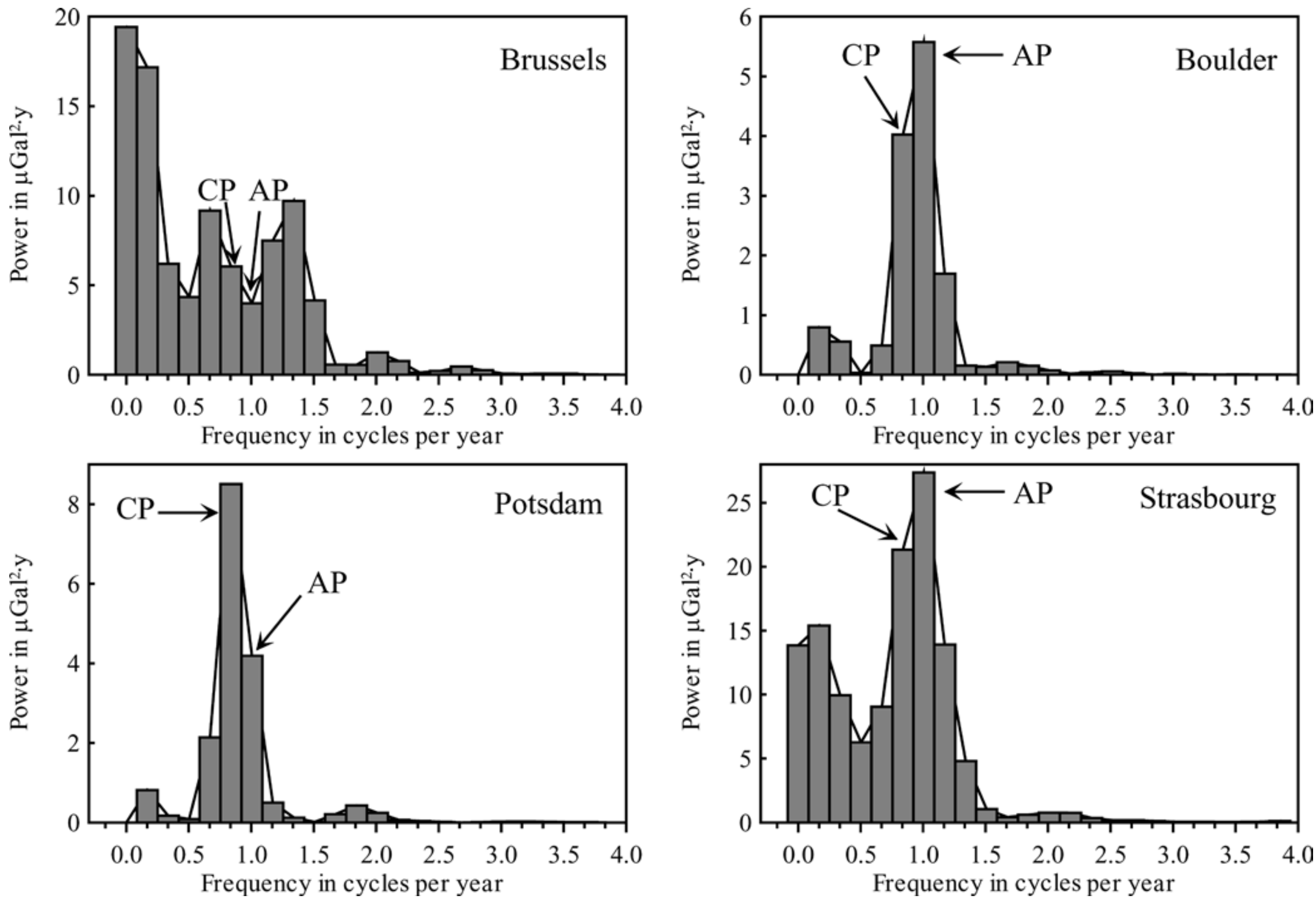

Fig. 3. Power spectral density estimates of the SG gravity residuals recorded at Brussels, Boulder, Potsdam and Strasbourg. CP refers to the Chandler period, and AP to the annual period

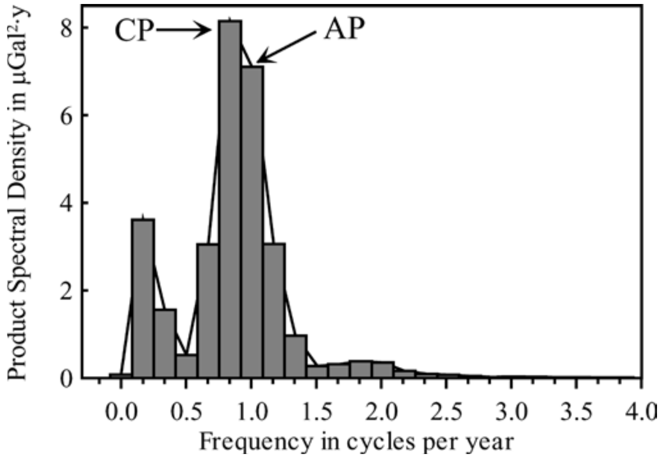

Fig. 4. Product spectral density estimates of the SG gravity residuals at GGP stations Brussels, Boulder, Potsdam, and Strasbourg

$$\frac{\Delta g_1(S,t)}{\sin 2\theta_S} = \sum_i A_{1Si}\cos(\omega_i t + \varphi_{1Si}) + C_s \cdot Pr(S,t) + \sum_{i=0}^{P} \alpha_i(S) \cdot t^{i-1} \quad (5)$$

where S stands for the SG site, ω_i is the angular frequency of the concerned signals including the annual and Chandler wobbles, as well as some long-period zonal tides if possible, φ_{1Si} the phase of the signal related to the station, A_{1Si} the latitude-independent part of the mean amplitude of a certain signal, C_S the remainder of the barometric admittance, and the third term on the right-hand side the long-term trend of the data set coming from barometric correction. Based on the least-squares (LS) technique, parameters A_{1Si}, φ_{1Si} and C_S were estimated using the gravity residuals observed at each SG station. The gravity variations $\Delta g_0(S,t,1)$, associated with polar motion for the rigid case, were also modeled as

$$\frac{\Delta g_0(S,t,1)}{\sin 2\theta_S} = \sum_i A_{0Si}\cos(\omega_i t + \varphi_{0Si}) + \sum_{i=0}^{P} \beta_i(S) \cdot t^{i-1} \quad (6)$$

The second term on the right-hand side is the long-term trend of the data set with β_i as the coefficients to be determined. Using the LS method, parameters A_{0Si} and φ_{0Si} were also determined. In the computation, the fitted parameters changed little until P reached 3. The gravimetric amplitude factor was evaluated as A_{1Si}/A_{0Si}, while the phase difference was attained as $\varphi_{1Si} - \varphi_{0Si}$. While N data sets were used, the gravimetric amplitude factors and phase differences were estimated as

$$\delta_i = \frac{\sum_{S=1}^{N} w_i(S) \cdot A_{1Si}}{\sum_{S=1}^{N} w_i(S) \cdot A_{0i}} \text{ and } \Delta\varphi_i = \sum_{S=1}^{N} w_i(S) \cdot (\varphi_{1Si} - \varphi_{0Si}) \quad (7)$$

respectively, where $w_i(S)$ is the weight function, which was given by

$$w_i(S) = \frac{1}{\varepsilon_{i1}(S)} \Big/ \sum_{S=1}^{N} \frac{1}{\varepsilon_{i1}(S)} \quad (8)$$

where ε_{i1} is standard deviation of parameters A_{1Si}. The fitted parameters are listed in Table 2.

In the procedure of parameter fitting, we did not use data from the early parts of the time series (i.e. 370 days at Brussels, 70 days at Boulder, 48 days at Membach, 100 days at Potsdam, and 58 days at Strasbourg) and those of last 207 days from Strasbourg, when the instrument may not have worked completely stably. Artificial removal of many irregular offsets, coming from the instrumental instabilities, led to the trends of these data being far away from those of the gravity variations caused by polar motion as shown in Fig. 1. Computation experiments indicated that the observations of the long-period gravity signals, including those related to polar motion, were highly sensitive to correction of the offsets. When these data were included, the fitted gravimetric amplitude factors for each station significantly changed in the incorrect direction. The best way to determine and then to remove the irregular offsets in the SG measurements is to carry out regular comparison observations between the SG and an absolute gravimeter at each site. According to the classical sampling theorem, the length of the data set from Membach, as well as that from Boulder, does not seem to be long enough to separate completely the Chandler and annual terms. In order to demonstrate the reliability of our computation, we artificially injected a signal, consisting of the Chandler and annual terms of different amplitudes and initial phases, into a random noise series of the same duration as the data set from Membach. Using the same method as described above, the signals were successfully retrieved.

Table 2. Gravimetric parameters of Chandler wave from the SG observations

Station	Used Data	A_1/μGal	δ	$\Delta\varphi$/(°)	C/(μGal · hPa^{-1})[a]
Brussels	Aug. 1987 ~ Sep. 2000	**3.4589** (±0.1471)	**1.1848** (±0.0504)	−**6.36** (±2.43)	**0.2813** (±0.0198)
Boulder	Jun. 1995 ~ Mar. 2001	**2.3405** (±0.0547)	**0.9481** (±0.0222)	**5.95** (±1.34)	−**0.5651** (±0.0241)
Membach	Sep. 1995 ~ May 2000	**3.0251** (±0.0449)	**1.2613** (±0.0187)	−**4.97** (±0.85)	−**0.2348** (±0.0062)
Potsdam	Oct.1992 ~ Oct. 1998	**3.7997** (±0.0632)	**1.2350** (±0.0205)	**5.28** (±0.95)	−**0.2584** (±0.0122)
Strasbourg	Sep. 1987 ~ Dec. 1995	**3.7925** (±0.2141)	**1.1767** (±0.0664)	**−27.04** (±3.23)	−**0.3760** (±0.0333)
All		**3.1176** (±0.0737)	**1.1613** (±0.0275)	−**1.30** (±1.33)	–

[a]The barometric admittances C are the sum of the results fitted from Eq. (5) and the corresponding values listed in Table 1.

The atmospheric admittance in the long-period band was determined (Table 2). Compared with the corresponding values (i.e., the mean barometric gravity admittances over the whole frequency range; Table 1), it was found that the atmospheric admittance showed obvious frequency-dependence and significantly changed with different observing periods and stations. Our results are consistent with those obtained in the previous studies (De Meyer and Ducarme 1991a; Merriam 1993; Crossley et al. 1995; Sun and Luo 1998; Xu et al. 1999). However, the case for Boulder seems to be exceptional. Compared with results obtained at the other stations and in previous studies, the absolute value of the barometric admittance was too large. The reasons should be investigated further. If the further correction of the barometric pressure was not taken into account in Eq. (5), it was found that the fitted parameters for Boulder significantly changed (the amplitude and amplitude factor of the Chandler term decreased about 10% in the wrong direction), while its influence on the fitted parameters for the other stations was negligible relative to their uncertainties. Considering the PSD estimates, it was found that the largest perturbations existed near the Chandler and annual periods in measurements of the station barometric pressure at Boulder. Hence, unsuitable barometric correction in the SG measurements may result in relatively large discrepancy in parameter estimation of these two signals.

The numerical results indicated that the latitude-independent part of the amplitude of the observed gravity variations at the Chandler period changed significantly at different stations and/or during different observing periods. It ranged from 2.3405 $\pm$ 0.0547 μGal (at Boulder from June 1995 to March 2001) to 3.7997 $\pm$ 0.0632 μGal (at Potsdam from October 1992 to October 1998), and had a mean value of 3.1176 $\pm$ 0.0737 μGal. Compared with amplitude of the CW-induced gravity variations predicted theoretically, it was concluded that the gravity changes at the Chandler period, measured with the SGs, predominantly came from polar motion.

The measured gravimetric parameters represent the integrated response of the elastic and damping properties of the Earth to external forces at the corresponding frequency. The results obtained in this study indicate that relatively large differences exist among the observed gravimetric parameters for the Chandler term at five SG stations. The amplitude factors ranged from 0.9481 to 1.2613, while the phase differences ranged from $-27°.04$ to $5°.95$ with relatively large uncertainties. It should be pointed out that the amplitude factor, observed with the SG at Boulder was 0.9481, less than unity, which is physically impossible. One of the main reasons for these results from the effects of relatively large local environment perturbations. From Fig. 3, it can be seen that there are very abundant long-period signals in the SG measurements from Brussels and Strasbourg, which may be related to regional perturbations. Especially at Brussels, the signals, associated with polar motion, were almost completely buried in the relatively large background noise; their spectral peaks were invisible in estimates of the PSD. Therefore, the fitted gravimetric parameters had relatively large uncertainties although the data sets from these two sites are much longer than those from the other stations. At Potsdam, although the Chandler term was the largest signal in the long-period band, compared with that related to the CW, the amplitude of the annual gravity signals seemed to be unacceptably small in the SG measurements (see below). This implied that there were considerably large local and/or global annual perturbations to significantly depress the signals related to the AW in the SG measurements in the opposite direction. As shown in Fig. 3, we may find that the Chandler and annual terms in the SG measurements from Boulder were the main signals in the long-period band. However, the energy at the Chandler period was much less than that at the annual period. In other words, there must be considerable annual perturbations in the SG measurements at Boulder. Meanwhile, the abnormal working status of the instruments, such as the injection of liquid helium in stated intervals, irregular offsets arising from occasional instability, and so on, may considerably influence the measurements of the long-period gravity signals, including those associated with Chandler wobble. Additionally, only the data of the station barometric pressure were involved in the atmospheric corrections to the SG gravity residuals, the loading characteristics of the global and local pressure were not taken into account.

For a certain global signal, all these effects may increase its amplitude in measurements and make the fitted parameters too large at one station, but decrease its amplitude and make the estimated parameters impossibly small at the other stations. As a result, a stacking procedure (taking the averages of different stations, which is described above, is the simplest way) may produce more reasonable and acceptable results. While combining the gravity residual series recorded at five SG stations, the effects of the local environment perturbations and systematic measurement errors of a single instrument were significantly depressed. Consequently, the gravimetric amplitude factor and phase difference at Chandler period are determined accurately to be 1.1613 $\pm$ 0.0737 and $-1°.30 \pm 1°.33$, respectively. Figure 4 may provide indirect evidence for the stacking effects in our parameter fitting (taking the weighted averages of different stations), although they were different stacking methods. After product stacking, the background noise on the long-period band effectively decreased compared with that for Brussels or Strasbourg; the energy distribution of the gravity residuals, observed with SGs, was similar to that of the predicted gravity variations caused by polar motion.

For the long-period solid-Earth tides, many studies show that the amplitude factor is slightly greater than unity (about 1.16), while the phase difference is a relatively small negative, for an anelastic Earth model (Wahr 1981; Mathews et al. 1995; Dehant et al. 1999). According to rough estimates (assuming that the oceanic pole tide is in static equilibrium, and there is no phase shift), loading effects of the oceanic pole tide increase the amplitude factor of the Chandler wave by about 0.025 (Loyer et al. 1999). However, the assumption of no phase shift is not always valid. Based on the NAO99 global oceanic model (Matsumoto et al. 2000), we computed the loading vectors of the long-period oceanic tides for Boulder. It was found the amplitude and phase of the loading vector were about 0.0023 μGal and $-117°.26$ for tidal wave S_a and 0.0032 μGal and 155°.25 for S_{sa}. Considering the fact that the potential perturbation caused by polar motion is similar to the luni-solar tidal potential, and the frequency of S_a is close to that of the Chandler term, the loading vector of the oceanic pole tide of the Chandler term was roughly estimated as follows: the phase was approximately taken as $-117°.26$ (the phase of oceanic loading vector for solid wave S_a); and the amplitude was obtained by multiplying 0.0032 μGal (the amplitude of the oceanic loading vector for solid wave S_{sa}) by the ratio of the theoretical amplitude of the Chandler wave to that of solid wave S_{sa} for the rigid case. In this case, the loading effects of the oceanic pole tide decreased the theoretical amplitude factor of the Chandler wave (1.16) by about 0.4%. In contrast, although the same method was used for Potsdam, here it was increased about 2.4%, which was close to the estimate of Loyer et al. (1999). Therefore, if the data sets, recoded at the stations distributed suitably on the Earth's surface, were simultaneously used, even the loading effects of the dynamic pole tide on the amplitude factor of the Chandler wave should be significantly eliminated. Although the estimated amplitude factor (1.1613 ± 0.0737) of the Chandler wave coincided with the theoretical value, its relatively large uncertainty did not allow any further discussion about the effects of the dynamic pole tide.

In addition, we also made an attempt to estimate the gravimetric amplitude factor and phase difference for the gravity variations associated with the annual polar motion. Unfortunately, no satisfactory result was obtained because some global and local environment perturbations, such as variations in sea level, underground and surface water and so on, obviously act at (or near) the annual period. The latitude-independent part of the amplitude of the annual gravity fluctuations, measured with the SGs, was 3.9744 ± 0.1394 μGal at Brussels, 2.4931 ± 0.0634 μGal at Boulder, 2.8462 ± 0.0391 μGal at Membach, 0.4711 ± 0.0655 μGal at Potsdam and 4.9842 ± 0.2100 μGal at Strasbourg. The gravimetric parameters of the gravity variations, related to the annual wobble, were estimated as being about 3.0610, 1.7084, 1.7734, 0.4246, and 4.3466 for the amplitude factors, and about $-135°.33$, -15°.38, 3°.17, $-99°.11$ and $-13°.24$ for the phase differences, respectively, at five SG stations. Simultaneously using the data at the all five sites, they were evaluated as 1.7925 ± 0.0522 for the amplitude factor and $-39°.52$ for the phase difference. The estimated amplitude factors were either impossibly little or impossibly large. Some other global annual perturbations may be responsible for the physical impossibility.

5 Conclusions

Stacking the long-term SG gravity observations, recorded continuously at multiple stations in different regions, may significantly depress the effects arising from local environment perturbations and systematic errors in the SG measurements. From our study, we confirmed that the gravity changes at the Chandler period, measured with the superconducting gravimeters, predominantly came from variations in the Earth's rotation axis, while the contribution of variations in the Earth's rotation to the gravity changes at the annual period was comparable to that of the other known and unknown global perturbations. Therefore, the gravimetric amplitude factor and phase difference of the gravity variations, associated with Chandler wobble, were determined accurately through this study by combining the SG measurements from five stations.

In the investigation of the gravity variations caused by polar motion, the loading effects of the local and global barometric pressure and the irregular offsets in the SG measurements, as well as the effects from annual global perturbations (e.g. global annual variations in sea level, hydrology cycle and so on), should be carefully considered. It should be pointed out that because the stations from which the SG data were used in this study were not globally distributed, local effects and the systematic errors in the measurements could not be completely eliminated and the retrieved parameters had relatively large uncertainties. The stacking continuous SG data of much longer duration, recorded at the globally distributed sites from the worldwide network of the GGP, may improve this study.

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References

Courtier N, Ducarme B, Goodkind J, Hinderer J, Imanishi Y, Seama N, Sun H, Merriam J, Bengert B, Smylie DE (2000) Global superconducting gravimeter observations and the search for the translational modes of the inner core. Phys Earth Planet Int 117: 3–20

Crossley DJ, Jensen OG, Hinderer J (1995) Effective barometric admittance and gravity residuals. Phys Earth Planet In 90: 221–241

Crossley DJ, Hinderer J, Casula G, Francis O, Hsu HT, Imanishi Y, Jentzsch G, Kääriäinen J, Merriam J, Meurers B, Neumeyer J, Richter B, Shibuya K, Sato T, Van Dam T (1999) Network of superconducting gravimeters benefits a

number of disciplines. EOS, Trans Am Geophys Un 8011(121): 125–126
Cummins PR, Wahr JM (1993) A study of the Earth's free core nutation using international deployment of accelerometers gravity data. J Geophys Res 98(B2): 2091–2103
Cummins PR, Wahr JM Agnew DC (1991) Constraining core undertones using stacked IDA gravity records. Geophys J Int 106: 189–198
Defraigne P, Dehant V, Hinderer J (1994) Staking gravity tide measurements and nutation observations in order to determine the complex eigenfrequency of nearly diurnal free wobble. J Geophys Res 99(B5): 9203–9213
Dehant V, Defraigne P, Wahr J (1999) Tides for a convective Earth. J Geophys Res 104: 1035–1058
De Meyer F, Ducarme B (1991a) Input–output analysis of the observations of superconducting gravity meter. In: Kakkuri J (ed) Proc 11th Int Symp on Earth Tides, Helsinki, Schweizerbastische Verlagsbuchhandlung, Stuttgart, pp. 531–554
De Meyer F, Ducarme B (1991b) Non-tidal gravity changes observed with a superconducting gravimeter. In: Kakkuri J (ed) Proc 11th Int Symp on Earth Tides, Helsinki, Schweizerbastische Verlagsbuchhandlung, Stuttgart, pp. 167–184
Dickman S (1988) The self-consistent dynamic pole tide in non-global oceans. Geophys J R Astr Soc 94: 519–543
Dickman S, Steinberg DJ (1986) New aspects of the equilibrium pole tide. Geophys J R Astro Soc 86: 515–529
Feissel M, Lewandowski W (1984) A comparative analysis of Vondrak and Gaussian smoothing techniques. Bull Geod 58(4): 464–474
Gross RS (2000) Combinations of Earth orientation measurements: SPASE97, COMB97 and POLE97. J Geod 73: 627–637
Loyer S, Hinderer J, Boy JP (1999) Determination of the gravimetric factor at the Chandler period from Earth orientation data and superconducting gravimeter observations. Geophys J Int 136: 1–7
Mathews PM, Buffett BA, Shapiro II (1995) Love numbers for a rotating spheroidal Earth: new definitions and numerical values. Geophys Res Let 22(5): 579–582
Matsumoto K, Takanezawa T, Ooe M (2000) Ocean tide models developed by assimilating TOPEX/POSEIDON altimeter data into hydrodynamical model: a global model and a regional model around Japan, J Oceanog 56: 567–581
Merriam JB (1993) The atmospheric pressure correction in gravity at Cantley Quebec. In: Hsu H-T (ed) Proc 12th Int Symp on Earth Tides, Science Press, Beijing, pp. 161–168
Richter B, Zürn W (1988) Chandler effect and nearly diurnal free wobble as determined from observations with a superconducting gravimeter. In: Babcock AK, Wilkins GA (eds) The Earth's rotation and reference frames for geodesy and geodynamics. Dordrecht: Kluwer Academic, pp. 309–315
Sato T, Fukuda Y, Aoyama Y, McQueen H, Shibuya K, Tamura Y, Asari K, Ooe M (2001) On the observed annual gravity variation and the effect of sea surface height variations. Phys Earth Planet Int 123: 45–63
Smylie DE, Hinderer J, Richter B, Ducarme B (1993) The product spectra of gravity and barometric pressure in Europe. Phys Earth Planet Int 80: 135–157
Sun HP, Luo SC (1998) Theoretical computation and detection of the atmospheric gravity signals. Chin J Geophys 41(3): 405–413
Tamura Y (1987) A harmonic development of the tidal generating potential. Mar Terrest Bull d'Info 99: 6813–6855
Vauterin P (1998) Tsoft: graphical & interactive software for the analysis of Earth tide data. In: Ducarme B, Paquet P (eds) Proc 13th Int Symp on Earth's Tides, Imprimerie Robert Louis, Bruxelles, pp. 481–486
Wahr JM (1981) Body tides on an elliptical, rotating, elastic and oceanless Earth. Geophys, J R Astr Soc 64: 677–703
Wahr JM (1985) Deformation induced by polar motion. J Geophys Res 90(B11): 9363–9368
Wenzel HG (1998) Earth tide data processing package ETERNA 3.30: the nanoGal software. In: Ducarme B, Paquet P (ed) Proc 13th Int Symp on Earth's Tides, Imprimerie Robert Louis, Bruxelles, pp. 487–494
Xu JQ, Sun HP (2003) Deformation response of a SNREI Earth to surface loads and tidal forces. Chin J Geophys 46(3): 465–477
Xu JQ, Xu HZ, Sun HP, Luo SC (1998) Analysis of the long-term gravity variations at Wuhan station. (in Chinese) Crus Deform Earthquake 18(3): 67–72
Xu JQ, Hao XH, Sun HP (1999) Influence of the atmospheric pressure on the tidal gravity observations at Wuhan. (in Chinese) Acta Geod Cartogr Sin 28(1): 75–79
Xu JQ, Sun HP, Luo SC (2002) Study of the Earth's free core nutation by tidal gravity data recorded with international superconducting gravimeters. Sci China Ser D 45(4): 337–347