The effect of periodic variations of thermospheric density on CHAMP and GRACE orbits

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In this paper thermosphere densities observed by the CHAMP and GRACE satellites and their orbital parameters are used to investigate the effect of periodic oscillations in thermospheric densities (7–27 days) caused by solar rotation and periodic magnetic activity on satellite orbits during 2003–2005. Two new results are obtained in this study. First, the response of the mean radius of the satellite orbit per revolution (MRPR) to the oscillations in the mean atmospheric density per revolution (MDPR) increased linearly with oscillation periods. Therefore, MRPR had a strong oscillation near the 27 day period. However, it had no obvious 7, 9, and 13.5 day oscillations, although there were strong oscillations at the same periods in MDPR. Second, there was a phase difference of $\frac{\pi}{2}$ between the oscillations of MRPR and MDPR. The phases of the oscillations in MRPR led the phases of the variations in MDPR. The correlation coefficient between the 27 day oscillations in MRPR and those in MDPR was 0.83 with a phase difference of −6.8 days for CHAMP; the correlation for GRACE was 0.67 with a phase difference of −6.4 days. The amplitudes of the oscillations in MRPR of CHAMP were larger than those of GRACE because GRACE had a higher orbit than CHAMP. These features are in good agreement with our theoretical analysis.


1. Introduction

[2] The orbits of Low Earth Orbit (LEO) satellites decay with time because of the atmospheric dragging force that is closely related to thermospheric density. The changes in thermospheric density create variable satellite drag, thus affecting human space activity such as spacecraft maneuver, lifetime, and its reentry prediction, and the identification and tracking of space objects [Doornbos and Klinkrad, 2006]. For instance, Smith et al. [1997] investigated orbit decays of the international space station caused by thermospheric density. On the other hand, thermospheric density retrieved from satellite drag data is a very important source for investigating thermospheric dynamics and developing empirical models of the thermosphere [e.g., Picone et al., 2002, 2005].

[3] Previous studies show that there are significant global-scale fluctuations of different periods in thermospheric density. They are mostly the results of solar and geomagnetic activity [e.g., Sutton et al., 2005; Forbes et al., 2005; Liu and Lühr, 2005; Lathuillère et al., 2008]. The oscillation in solar radiation induced by solar rotation causes 27 day and its harmonic variations in thermospheric densities [e.g., Eastes et al., 2004; Guo et al., 2007]. Lei et al. [2008a, 2008b] showed that solar wind high-speed streams and their associated geomagnetic activity can drive 7, 9 and 13.5 day oscillations in thermospheric densities by the energy and momentum coupling within the solar wind-magnetosphere-thermosphere/ionsphere system.

[4] Thus the question needs to be answered is that how the orbits of satellites change with these thermospheric density variations. Walterscheid [1989] studied the effect of the solar cycle variation of thermospheric density on satellite lifetime, and pointed out that short-term changes in thermospheric density might have important consequences in satellite tracking. Nevertheless, there have been very few studies on this subject, to our best knowledge.

[5] In this paper, we use both the orbital height data and the thermospheric density data from the Challenging Minisatellite Payload (CHAMP) satellite and the Gravity Recovery and Climate Experiment (GRACE) satellite to investigate variations of satellite orbits caused by the periodic changes of thermospheric density. In section 2 we will describe the data set and analysis method. Results will be shown in section 3. Discussion of the results will be presented in section 4 and summary is given in section 5.

2. Data Set and Analysis Method

[6] The CHAMP satellite was launched on 15 July 2000 to a polar, near-circular orbit (the initial altitude was about...
430 km) with an inclination of 87.3° [Reigber et al., 2002].

The GRACE mission contains twin satellites (GRACE A and GRACE B) which were launched on 17 March 2002. They are in a circular orbit (with an eccentricity less than 0.005) with an initial altitude of about 500 km. The inclinations of the orbits of the two satellites are about 89 degrees. These two satellites stay in coplanar orbits separated by about 220 km. In this study, we use thermospheric mass densities derived from the accelerometer data and the orbit parameters from the CHAMP and GRACE A satellites. The procedure of deriving thermospheric mass densities form the CHAMP and GRACE accelerometer data along satellite tracks was described in detail by Sutton et al. [2005, 2007, 2009] and Bruinsma et al. [2004]. In the present work, we used the latest data set from Sutton et al. [2009]. The largest sources of error in accelerometer density estimation are the drag coefficient $C_D$ and the atmospheric wind. The $C_D$ model used to derive thermospheric density depends on solar activity as in situ composition and temperature from the MSIS model are used to estimate the variations of the $C_D$ parameter. Winds are not considered in the derivations of thermospheric density because there are no independent measurements of the wind vector [Sutton et al., 2009]. It is assumed here that the effects of winds are not severe since we use orbital averaged data in this study.

[7] In addition, total solar EUV radiation from 30 nm to 120 nm observed by the SEE instrument (Solar EUV Experiment) onboard the TIMED (Thermosphere, Ionosphere, Mesosphere, Energetics and Dynamics) satellite is used as a proxy for solar radiation.

[8] The thermospheric drag force acts on a satellite in the opposite direction of the satellite orbital motion and is given by [e.g., King-Hele, 1987; Wertz and Larson, 1999; Montenbruck and Gill, 2001]

$$F_D = \frac{1}{2} \rho AC_D v^2,$$

where $A$ is the satellite’s cross-sectional area perpendicular to the direction of the motion, $\rho$ is the atmospheric density at the location of the satellite, $v$ is the satellite velocity with respect to the corotating atmosphere, $C_D$ is a dimensionless drag coefficient that describes the interaction between the atmospheric particles and the satellite. The above equation shows that atmospheric density is an important parameter for satellite drag and its variations can produce changes in satellite orbits.

[9] Although CHAMP and GRACE satellites are in near circular orbits, there are still tens of kilometer differences in orbit heights between the satellite apogee and perigee. For instance, there were about 20 km differences for CHAMP in 2003. Therefore, the distance between the satellite and the Earth center varies along each satellite orbit. In this paper, we use the averaged distance between the satellite and the
center of the earth of each revolution of the orbit. This distance is defined as the mean radius of the satellite orbit per revolution (MRPR). Similarly, we also use the mean atmospheric density per revolution (MDPR), which is the averaged atmospheric density for each revolution of the orbit, in our analysis.

3. Results

[10] Figure 1 shows temporal variations of the mean atmospheric density per revolution (MDPR) and the mean radius of the satellite orbit per revolution (MRPR) of CHAMP and GRACE (Figure 1, middle and bottom) between 2003 and 2005. The $Dst$ index and solar EUV flux are also given (Figure 1, top). There were several strong magnetic storms from 2003 to 2005. For instance, two of them took place in October (minimum $Dst = -350$ nT) and November (minimum $Dst = -420$ nT) of 2003, respectively. The atmospheric densities observed by CHAMP and GRACE responded to these two storms with changes of 200–400%, as already reported by Sutton et al. [2005]. In 2004, two strong magnetic storms occurred near day 210 (minimum $Dst = -200$ nT) and day 313 (minimum $Dst = -380$ nT). The atmospheric densities at the altitudes of CHAMP and GRACE had profound responses to these storms. Meanwhile, these magnetic storms had strong influence on the altitude of satellite orbits. For instance, during
the storm of October 2003, the mean altitude of the CHAMP orbit decreased by about 500 m. So far most of the studies have focused on the thermospheric density response to these major storms [e.g., Sutton et al., 2005; Forbes et al., 2005]. The change of satellite orbits caused by geomagnetic storms, however, has not been fully investigated. In particular, there have not been many investigations on the satellite orbit responses to recurrent geomagnetic activity caused by solar wind high speed streams and corotating interaction regions as well as periodic solar EUV variations that are related to solar rotation. In this paper, we will focus our studies primarily on the effect of solar rotation and recurrent magnetic activity on thermospheric density and, consequently, on the satellite orbit.

Figure 2. (continued)
In order to investigate the characteristics of the periodic oscillations, Lomb-Scargle (LS) periodograms [Lomb, 1976; Scargle, 1982] of the atmospheric density, satellite orbit altitude, solar EUV radiation, and the geomagnetic activity index (Kp) for 2003, 2004, 2005, and the total spectra for 2003–2005 are calculated and shown in Figure 2 for CHAMP and GRACE. The dominant oscillation in the EUV flux had a period of around 27 days, which was the result of solar active regions rotating into the field view of the Earth for each solar rotation. The strongest oscillations in the mean atmospheric density per revolution (MDPR) and the mean radius of the satellite orbit per revolution (MRPR) of both satellites were also at the period of about 27 days. The quasi–27 day oscillations in 2003 in EUV, MDPR, and MRPR were the strongest in these 3 years. It is evident that in 2003 there was a distinct peak at 29 days for EUV and a broad peak between 26 and 30 days for Kp. In 2004, EUV had a broad peak around 27 days, but Kp did not. In 2005, Kp had a peak at 29 days, but EUV did not have one. The 29 day and 24 day peaks in EUV in the total spectra of 3 years could be the results of the emerging and disappearing of different active regions that changed the

Figure 3. The band-pass filtered time series of EUV flux, the mean atmospheric density per revolution (MDPR), and the mean radius of the satellite orbit per revolution (MRPR). From top to bottom, first panel, EUV flux and CHAMP’s density; second panel, CHAMP’s density and CHAMP’s mean satellite orbital radius; third panel, EUV flux and GRACE’s density; fourth panel, GRACE’s density and GRACE’s mean satellite orbital radius.

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regular variations of solar EUV radiation with solar rotation, and introduced the multipeak spectral structures.

[12] In addition, for CHAMP and GRACE there were quasi-9 day and 13.5 day oscillations in MDPR and the Kp index. The quasi-9 day oscillations were associated with variations of high-speed solar wind and the resultant geomagnetic activity [Lei et al., 2008a, 2008b]. On the other hand, the 17 day spectral peak that occurred in these years appeared to be associated with the subharmonics of the quasi-9 day variations of Kp.

[13] Figure 2 also shows that the spectra of EUV, MDPR, and MRPR around the 27 day peak had very similar features in these 3 years. One striking feature of the CHAMP and GRACE MRPR is that the response of MRPR to the short-period oscillations in MDPR (9 day and 13.5 day) was much weaker than that to the longer-period oscillations (27 day). On the other hand, for GRACE, there was a wealth of short-period (period of several days) oscillations in MRPR. Most of these oscillations were not seen in MDPR. The possible reasons for this are discussed in section 4.

[14] We now focus our discussion on the strongest oscillations in both MDPR and MRPR with a period of about 27 days. In order to investigate the effect of 27 day oscillation of the solar forcing on the upper atmosphere density and satellite orbit, all time series (the mean atmospheric density, the mean radius of satellite orbit, and EUV flux) were first processed to minimize variations at periods significantly longer and shorter than the 27 day solar rotation period.

[15] Figure 3 gives the results for solar EUV flux, atmospheric densities observed by CHAMP and GRACE and orbital radiuses of the two satellites after a band-pass filter, which was centered at the period of 27 days with half-power points at 22 and 32 days, was applied. It is obvious that both the atmospheric densities and the satellite orbit radiuses had a strong response to the 27 day oscillation in solar radiation. High correlations were found between MDPR, MRPR, and EUV, especially when a strong quasi-27 day periodicity was present. The 27 day variations in atmospheric densities had lags following the oscillation in solar radiation of the same periods. On the other hand, the rates of temporal change of satellite orbit heights were anticorrelated with thermospheric densities.

[16] The amplitudes of the oscillations in the MDPR and MRPR of CHAMP were larger than those of GRACE. Given that the altitude of the GRACE was about 100 km higher than that of the CHAMP the effect of thermospheric drag was weaker at the GRACE altitude. For instance, the oscillation of MRPR was about 0.1 km for the CHAMP, while it was about 0.05 km for the GRACE during the first half of 2003.

[17] In order to investigate the phase relationship between the oscillations in solar radiation, atmospheric density and satellite orbital radius, the correlation coefficients between these parameters are computed and shown in Figure 4. It can be seen that the correlation coefficients between the mean atmospheric density per revolution (MDPR) and EUV were 0.88 with a phase lag of 0.8 day for CHAMP, and 0.89 with a phase lag of 0.7 day for GRACE. The two satellites had almost the same correlation coefficient between thermospheric density and EUV for the 27 day oscillation. This is very close to the results of Guo et al. [2007], which showed that the time delay between changes of solar irradiance and those of thermospheric densities was about 1 day. For the correlation between the mean radius of the satellite orbit per revolution (MRPR) and the mean atmospheric density per revolution (MDPR), CHAMP gave the best correlation coefficient of 0.83 with a phase lag of −6.8 days. GRACE gave the best correlation coefficient of 0.67 with a phase lag of −6.4 days. The phase lags of two satellites were almost the same. The negative phase lag implies that the phase of the oscillation of MRPR was ahead of the phase of the fluctuation of MDPR, although the fluctuation of MRPR was caused by the oscillation of thermospheric density. For the correlation between the mean radius of the satellite orbit per revolution (MRPR) and the oscillation of EUV, CHAMP showed a maximal correlation coefficient of 0.75 with phase lags of −6.0 days. GRACE had the best correlation coefficient of 0.57 with a phase lag of −5.6 days.

[18] From the time series of solar EUV, the mean atmospheric density and the radius of satellite orbit we can see that the intensities of their oscillations varied with time (Figure 3). In order to investigate the variation of their correlations, Figure 5 gives the temporal changes of the correlation between MDPR and MRPR for the two satellites.
from 2003 to 2005. It is clear that the phase lag of the correlation peak remained as approximately a constant during these 3 years. Correlations tended to increase during intervals of strong quasi-27 day oscillations in EUV, MDPR, and MRPR. Figure 5 also shows that the correlation coefficient between MDPR and MRPR of CHAMP was larger than that of GRACE. We also calculated the correlations between EUV and MDPR, EUV and MRPR for the two satellites, and obtained similar results.

4. Discussion

[19] The positive phase lag of the fluctuation in thermospheric density relative to the oscillation in solar radiation was discussed in many studies [e.g., Eastes et al., 2004; Guo et al., 2007]. In this section we focus on the explanation of the phase relationship between the oscillations in the radius of the satellite orbit and atmospheric density. In the analysis, we only study the influence of atmospheric drag on the satellite orbit. The effect of Earth’s gravitational perturbations (asphericity of the potential field) on the orbit of LEO satellite is ignored [e.g., King-Hele, 1987].

[20] The changes in the mean radius of the satellite orbit per revolution (MRPR) which, according to equation (6–24) of Wertz and Larson [1999], is

$$\Delta r_{MRPR} = -2\pi \left(\frac{C_5}{r_0}\right) m r_0^2,$$

where $m$ is the satellite mass, $r_0$ is the averaged radius of the satellite orbit during the period of our interest (for instance, from 2003 to 2005 in this study).

[21] A satellite in a circular orbit experiences a centripetal acceleration, which equals to gravitation:

$$F_r = -\frac{mv^2}{r_0} = -\frac{GMm}{r_0^2},$$

where $M$ is the mass of the Earth, $G = 6.673 \times 10^{-11} \text{ (m}^3 \cdot \text{kg}^{-1} \cdot \text{s}^{-2})$ is the gravitational constant. Therefore, the speed of the satellite is

$$v = \sqrt{\frac{GM}{r_0}}.$$
Thus, the period of the satellite orbit per revolution is
\[ \Delta t = \frac{2\pi r_0}{v} = \frac{2\pi r_0}{\sqrt{GM}} \]

Form equations (2) and (5), the differential equation for the MRPR is
\[ \frac{dr_{MRPR}}{dt} = -\rho AC_D \frac{\sqrt{GM}}{m} \sqrt{r_0}. \]

Equation (6) indicates that the differential of the mean radius of the satellite orbit per revolution with time is anticorrelated with atmospheric density. If the atmospheric density has an oscillation with a period of \( T_r \),
\[ \rho = \rho_0 + \varepsilon e^{\omega t}, \]
where \( \rho_0 \) is the background density, \( \varepsilon \) is the amplitude of the oscillation, \( \omega = 2\pi T_r \) is the frequency of the oscillation, \( T_r \) is the period of the oscillation, and \( i = \sqrt{-1} \). The solution of equation (6) is
\[ r_{MRPR}(t) = r_{r=0} - \rho_0 AC_D \frac{\sqrt{GM}}{m} \sqrt{r_0 t} + \frac{\varepsilon AC_D}{\omega} \frac{\sqrt{GM}}{m} \sqrt{r_0} \exp\left[ i \left( \omega t + \pi \right) \right]. \]

where, \( r_{r=0} \) is the initial radius of the satellite orbit.

The first term of above equation,
\[ r_{MRPR}(t) = r_{r=0} - \rho_0 AC_D \frac{\sqrt{GM}}{m} \sqrt{r_0 t}, \]
is the decay of the satellite orbit height due to the background thermospheric density drag for a fixed atmospheric density. This term results in about a 70 km decline of the CHAMP satellite orbit height from 2003 to 2005, and about 20 km satellite orbit decline for GRACE (Figure 1).

The second term in the right of equation (7) is the deviation of the mean radius of satellite orbit per revolution (MRPR) caused by periodic oscillations in thermospheric density, which is the focus of this study and can be expressed as
\[ \delta r_{MRPR}(t) = \frac{\varepsilon \bar{R}}{\omega} \exp\left[ i \left( \omega t + \pi \right) / 2 \right], \]

where, \( \bar{R} = AC_D \frac{\sqrt{GM}}{m} \sqrt{r_0} \) is a constant.

From above equation, we can see that there is a \( \pi/2 \) phase difference between the oscillations in thermospheric density and those in the radius of the satellite orbit. The phase of the satellite orbit oscillation is \( \pi/2 \) (6.75 days for the 27 day oscillation) ahead of the thermospheric density oscillation. This is consistent with the variation of the orbits of CHAMP and GRACE shown in Figures 3 and 4, their phase lags are –6.8 days and –6.4 days, respectively.

It is worth noting here that the phase delays discussed above are not directly related to the causal relationship between the oscillations in thermospheric densities and those of satellite orbit heights. In fact, a close exam of the temporal variations of the changes of the MDPR and MRPR deviations given in Figure 3 shows that the changes in MDPR were the cause of the changes seen in MRPR. In general, when the deviation of MDPR becomes positive (enhanced thermospheric density), MRPR begins to decrease. This decrease in satellite orbital height continues till the deviation of MDPR becomes negative (depleted thermospheric density). The opposite situation or increase in MRPR then occurs. Thus, the positive and negative peaks of the deviation of MRPR correspond to the time when the deviation of MDPR is about zero (~6.75 phase shift for a 27 day oscillation). From equation (6), the negative phase lag of about \( \pi/2 \) is not a spurious product of data analysis, instead, it shows that the differential of the radius of the satellite orbit with time is negatively correlated with atmospheric density [e.g., Burns, 1976; King-Hele, 1987; Wertz and Larson, 1999].

Equation (8) also shows that the amplitude of the oscillation of MRPR was directly proportional to both the period \( T \) and the amplitude \( \varepsilon \) of the thermospheric density oscillation. From Figures 2 and 3, the amplitude of the oscillation of CHAMP’s MRPR was larger than that of GRACE since the amplitude of MDPR at the altitude of CHAMP was larger than that of GRACE. Figure 6 gives the change of the ratio between the amplitude of the MRPR fluctuation and the amplitude of the MDPR oscillation above the 95% significance level, \( \eta \), with the period of the fluctuation for the CHAMP and GRACE satellites.

For CHAMP, it is evident that \( \eta \) increases with the period of the oscillation, which is consistent with equation (8). This indicates that the response of MRPR to fluctuations of MDPR is stronger for the longer-period (27 days) oscillations than for the shorter-period fluctuations, for instance, the 9 day oscillation. This is probably the main reason that in Figure 2 we observe much smaller amplitudes for the 7, 9 and 13.5 day oscillations in MRPR, although there were relatively stronger oscillations in both the Kp index and MDPR of the same periods. For GRACE, \( \eta \) shows the same trend as that for CHAMP. The amplitude also increases with the period of the oscillation. However, the data is more scattered. This might be related to the oscillations of short periods (several days) as shown in Figure 2. These orbital oscillations were not seen or very weak in thermospheric density, indicating that they might not be caused by density oscillations. The orbit of GRACE is higher than that of CHAMP by about 100 km, thermospheric density is less dense at the GRACE orbit. Other factors, such as solar radiation pressure, solid and ocean tides and nonuniform gravity, may not be neglected when compared to the effect of atmospheric drag. They may also induce periodic oscillations to the GRACE orbit. Further analysis is needed to fully understand the exact causes of short-period oscillations in the GRACE orbits.

5. Summary

The CHAMP and GRACE observations provide a good opportunity for investigating the effects of solar and...
magnetic activity on the LEO satellite orbit. In this paper thermosphere densities observed by the CHAMP and GRACE satellites and their orbital parameters during 2003–2005 are used to investigate the periodic oscillations (7–27 days) of the satellite orbital altitudes caused by the effect of solar rotation and periodic solar wind and magnetic activity on thermospheric density. The main new results of this study are as follows.

[28] 1. There were abundant oscillations in thermospheric densities seen by CHAMP and GRACE between 2003 and 2005. The oscillations with a period of quasi-27 days were caused by the oscillations in solar EUV radiation, while those with periods of quasi-7, 9 and 13.5 days were the results of recurrent magnetic activity. Both observations and theoretical analysis indicate that the response of the satellite altitude (MRPR) to thermospheric density oscillations depended on the period of the oscillation. The response was stronger for oscillations with longer periods than those with shorter periods. Thus, the CHAMP and GRACE orbits did not have obvious 7, 9 and 13.5 day oscillations between 2003 and 2005, although there were strong oscillations of these periods in thermospheric density caused by solar wind high-speed streams and corotating interaction regions in these years.

[29] 2. Both the observations of CHAMP and GRACE and theoretical analysis suggest that there was a phase difference of $\pi/2$ (for instance, 6.75 days for the 27 day oscillation) between the oscillations of the mean radius per revolution of satellite orbit and the mean atmospheric density per revolution. The phases of the oscillations in the satellite orbital radius led the phases of the variations in atmospheric densities. There was a good correlation between 27 day oscillations in the mean radius of satellite orbit and those in the mean atmospheric density. The correlation coefficient was 0.83 with a phase lag of $-6.8$ days for CHAMP and 0.67 with a phase lag of $-6.4$ days for GRACE. Because the phase difference between the 27 day oscillation of thermosphere density and the corresponding oscillation in solar EUV flux had a time delay of about 0.8 day, the phase difference between oscillations in satellite orbital radius and solar EUV radiation was $-6.0$ days for CHAMP and $-5.6$ days for GRACE.

[30] In addition, the amplitudes of the oscillations in the mean radius of satellite orbit per revolution of CHAMP are larger than those of GRACE. The orbit altitude of GRACE is about 100 km higher than that of CHAMP. Thus, the effect of thermospheric drag satellite orbit is weaker at the GRACE altitude.

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