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EXPRESS LETTER

Wavelet characterization of external magnetic sources as observed by CHAMP satellite: evidence for unmodelled signals in geomagnetic field models

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SUMMARY

We apply continuous wavelet transform technique to the full decade (2001–2010) of CHAMP vector magnetic data from 55417 tracks, to search for evidences of external source field signatures that are either misunderstood or ignored in modern magnetic field models. We show that satellite magnetic time-series, after subtracting the main and lithospheric field contributions, exhibit several external source signals. Other than the diurnal, 27-day, and annual periodicities, we also have observed the 210-day periodicity, in the external magnetic field. Central to these observations is the local time dependency of 27-day variations, which suggests that the purely zonal source model, generally considered for the estimation of electromagnetic induction response is inadequate. We discuss the origin and characteristics of 210-day periodicity, although its geophysical significance needs to be fully ascertained. A better understanding of the external fields as seen at satellite altitude is a prerequisite for an optimum exploitation of Swarm multi-satellite mission, which is scheduled for launch in 2013.

Key words: Time-series analysis; Wavelet transform; Magnetic field; Satellite magnetics.

1 INTRODUCTION

CHAMP has been one of the most successful satellite missions for Earth's magnetic field studies. It was the German low-Earth orbit (LEO) mission, orbiting within an altitude range of 454 to 300 km from the beginning to the end of the mission, operating for more than a full decade (2000 July–2010 September). Progresses in our understanding of the Earth's internal field (Lesur *et al.* 2008, 2010; Maus *et al.* 2008), and external field (Lühr & Maus 2010) resulting from the study of the CHAMP data set have been significant. For a collection of articles on various applications of CHAMP data (Earth's gravity field; Earth's magnetic field; neutral atmosphere and ionosphere) see Reigber *et al.* (2005), and for a recent review on CHAMP magnetic field experiment see Mandea *et al.* (2010).

The European Space Agency (ESA) will soon be launching its Swarm mission, to further provide the best ever survey of the geomagnetic field and its temporal evolution and to gain new insights into improving our knowledge of the Earth's interior and climate. The Swarm concept consists of a constellation of three satellites, in which, two satellites orbit at an altitude of 450 km (side by side, with a separation of 150 km) and the third one at a higher altitude of 550 km. These three satellites thus orbiting at different altitudes and local times simultaneously, facilitate to improve the understanding and modelling of the spatio-temporal variations of the geomagnetic field.

Global geomagnetic field models constitute the temporal core field, the lithospheric field and a rough representation of the external field. The dominant component is the core or main field, generated by magneto-hydrodynamic processes operating in the Earth's fluid outer core. The lithospheric field, as it suggests, originates from the Earth's lithosphere and the external field, often varying rapidly in time, originates from extra-terrestrial current systems located in the ionosphere and magnetosphere, driven by the activity of the Sun.

Global magnetic field models generally utilize night-side, quiet time satellite data as well as observatory magnetic data to minimize the ionospheric and magnetospheric effects. However, the contribution of the external fields remains poorly understood. By applying continuous wavelet transform (CWT) to the night-side, mid-latitude CHAMP data confining to the local time (LT) window of 18:00 hr to 06:00 hr, this paper demonstrates that a series of unmodelled low-frequency signals exist in the external magnetic field. These signals, if not accounted for, might result in developing inaccurate global models.

In this paper, we address two important issues concerning the characterization of external magnetic sources: (i) the LT dependency of 27-day variation and (ii) the presence of 210-day periodicity.

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2 CHAMP DATA PROCESSING

CHAMP vector magnetic data of 1 Hz sampling interval, from a total of 55417 tracks, spanning from 2001 January 1 to 2010 September 3, are used in this study. Data selection is limited to geomagnetic mid-latitude region ($\pm 50^{\circ}$) to minimize the effects of polar cap ionospheric currents, high latitude auroral electrojet and field aligned currents. To reduce the influence of ionospheric currents, only night-side data with a 12-hour LT window of 18:00 to 06:00 hr centred on local midnight are used. The broad LT window leads to a large data volume and ensures full nighttime coverage. It also helps in identifying LT dependencies of the field variations if any. Since the objective is to characterize the large-scale perturbation of the field on all days (disturbed or quiet), no activity-based selection criteria were imposed on the data.

As a first step towards characterization of the external field, the slowly varying core field (up to spherical harmonic (SH) degree, $l = 14$) and the lithospheric field (up to $l = 60$) are removed from the data using GRIMM-2 (Lesur *et al.* 2010). For $l > 60$, the amplitude of lithospheric field is assumed to be small and negligible. Next, following the Iterative Reweighted Least Squares approach (Farquharson & Oldenburg 1998), we have estimated the stable outer magnetospheric contribution to be 7.39 nT, determined along the Z direction in Geocentric Solar Magnetospheric (GSM) reference frame. This was subtracted from the field residuals before further analysis. The resultant data were averaged for each orbit after rotating the residuals to Solar Magnetic (SM) reference frame. Orbit-averages maximize the contribution from the large-scale external field (SH deg. 1) and reduce the influence of residual lithospheric signals and localized perturbations of the magnetic field. Rotation to SM frame was necessary as the data in this frame represents the fields corresponding to inner magnetosphere. This processing has resulted in three time-series (one for each vector direction) with a sampling rate of 1.5432 hr ($\sim$90 min). The orbit-averaged values corresponding to SM frame were used for further analysis. Although these time-series are strongly dominated by the large-scale external field, they are likely to contain smaller contributions of internal origin as well. We next have applied CWT to the three time-series (Balasis *et al.* 2005, 2006) to understand the time-localization of different frequency characteristics of external field. The time-series have been analysed using Morlet wavelet, Mexican hat wavelet, PAUL wavelet and DoG (Derivative of Gaussian) wavelet. Among them, we chose Morlet wavelet as it has provided the finest resolution of the periodicities discussed in this study (Balasis *et al.* 2005, 2006; Mandea & Balasis 2006; Balasis & Mandea 2007).

3 RESULTS

CWT revealed prominent continuous and transient geomagnetic features present in the field residuals. Fig. 1 shows wavelet power spectra of orbit-averaged time-series along X, Y and Z SM-directions and that of the IMF By component. It shows higher powers in all the three components during the solar maximum period (2001–2006) compared to the other years, further confirming the direct influence of solar cycle on the geomagnetic field variations. The CWT scalogram plots also reveal that the resolution of long period signals is very good, while that of the short periods is relatively poor in all the three components. Fig. 2 depicts the zoomed-in portion of Fig. 1 corresponding to longer periods, which facilitates a better understanding of the dominant spectral signatures of these well resolved signals. The observed periodic signals are extracted by applying inverse wavelet transform to the CWT coefficients of the original signal. Their respective amplitudes together with their percentage contributions to the original time-series are given in the description of each periodicity.

3.1 Short periodicities

The spikes at short periods in the scalogram plots (Fig. 1) are due to geomagnetic activity associated with the storm-time magnetosphere, which are present in the signal since no special care was taken to subtract any Dst-driven signal as Balasis & Egbert (2006) did for observatory data. Therefore, the high intensity spikes correspond to magnetic storm events.

3.2 1-day periodicity

The daily signal is clearly visible in both X- and Y-components but not in Z- and IMF-By components (Fig. 1). The amplitude of

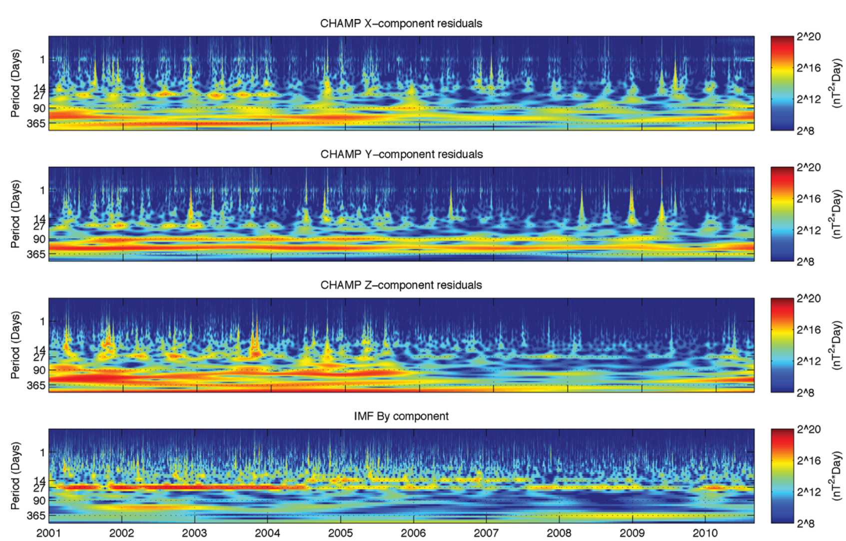

Figure 1. From top to bottom: wavelet power spectra of CHAMP X-, Y- and Z-residuals and IMF-By component, depicting the time evolution of various periodicities.

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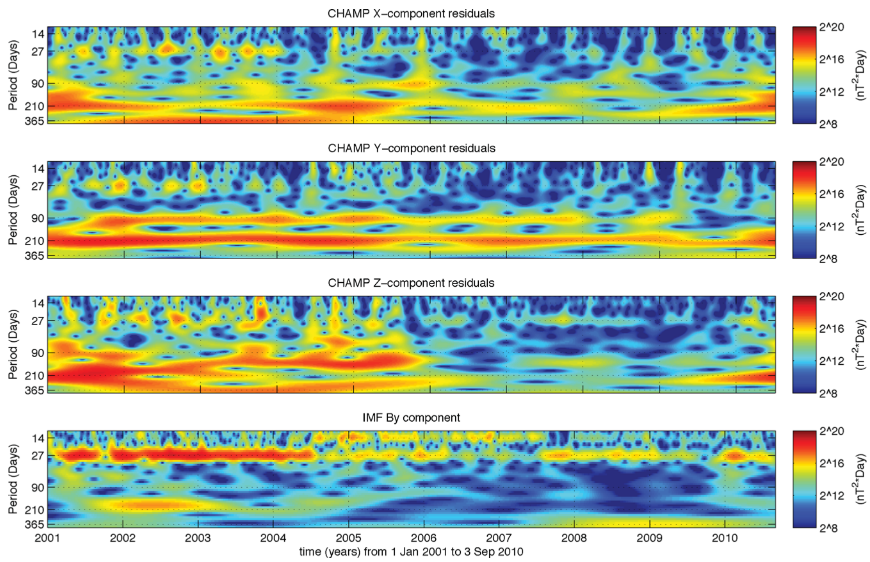

Figure 2. Same as Fig. 1, but for longer periods.

this signal observed in the X-component is 0.01 nT in average and constitutes 0.27 per cent of the original time-series. Also, the daily variation intensity even during the solar maximum period may be too weak in Z, to be resolved by the Morlet wavelet, while this signal is totally absent during the solar minimum period, beyond the year 2006.

3.3 27-day periodicity

The 27-day periodic signal, which signifies the recurrence tendency of the geomagnetic storms, has higher energy during active periods and slowly decreases in intensity with time, indicating the solar cycle influence. This signal that represents the solar rotation period is seen as an intermittent temporal structure in all the residuals and as a continuous feature in the IMF-By component (Fig. 2). The amplitude of this signal is 0.11 nT in average but can take much larger values. It constitutes 2.47 per cent of the original signal, when observed from the X-residuals. The intermittent nature of this signal indicates LT dependency. Fig. 3 shows the CWT coefficients of this signal observed in the residuals and their longitudinal distribution depicting the LT dependency. The IMF-By signal is directly linked to the IMF sectors, which are defined by the spiral nature of the IMF (Wilcox & Ness 1965). From the middle of the year 2004 to the middle of 2007, the usual two sector structure becomes more complex with four sectors, during which, the intermittent temporal structure observed in the vector components is weaker. The transformation of IMF from two sectors to four sectors leads to a dominant signal at shorter periods, around 13.5 d. The 27-day periodic signal seen in all the components is in agreement with the observation of Lesur *et al.* (2005), where they observed a correlation between IMF-By and the east–west component variations in geocentric coordinate system. The east–west component is a complex combination of both the X and Y components in the SM coordinate system.

3.4 90-day periodicity

This periodicity is prominently seen in Y-residuals at all years (Fig. 2) with an amplitude of 0.36 nT in average, that corresponds to a contribution of 8.16 per cent to the original signal. Interestingly, while this signal appears to be smeared in X-component with in-

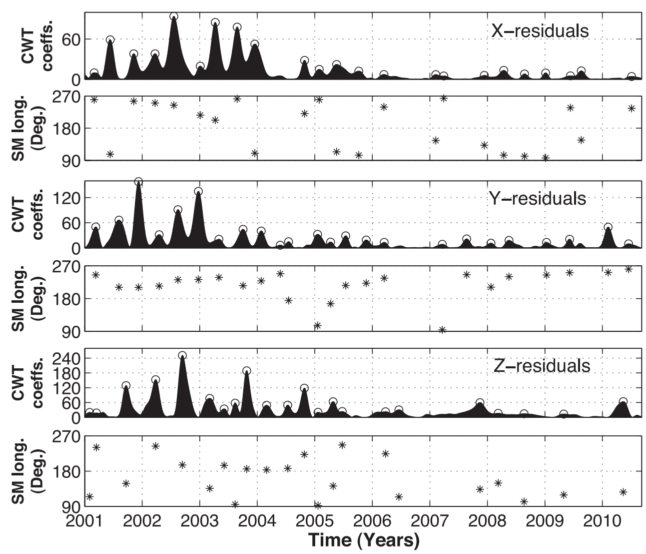

Figure 3. CWT coefficients of 27-day periodic signal for the three vector components in SM frame and their longitudinal distribution as observed by CHAMP. The shaded portion (odd number plots) represents the wavelet correlation coefficient and the circles at the apex indicate the peaks considered for the analysis. The even number plots represent the LT dependency of 27-day periodic signal as a function of SM longitude (see text for details).

termittent traces, it is prominent in the Z-residuals during the solar maximum period.

3.5 210-day periodicity

The amplitude of the reported 210-day periodic signal observed in the Y-residuals is 1.17 nT in average and constitutes 26.30 per cent of the original signal. Although this periodicity is known to have some significance in cosmic ray intensity data corresponding to the solar maxima (Mavromichalaki *et al.* 2003; Chowdhury *et al.* 2010) and in an interrelation between solar activity and the terrestrial thermospheric cooling rate (Mlynczak *et al.* 2007), we found this periodicity for the first time, in CHAMP satellite geomagnetic data also (Fig. 2). The distinction between the 210-day periodicity and

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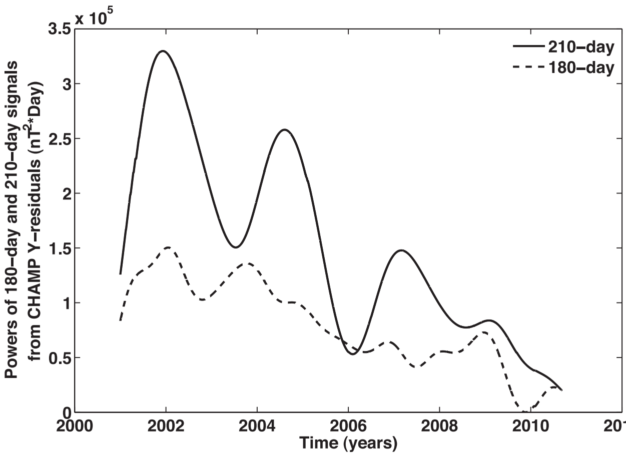

Figure 4. The powers of 210- and 180-day periodic signals, that are extracted from Fig. 2. The 210-day signal exhibits some periodic nature with almost twice the power of the 180-day signal. The time evolution of these two periodic signals suggests a link to the solar cycle activty.

the geomagnetic semi-annual (180-day) variation is shown in Fig. 4 through the wavelet power spectrum of CHAMP data.

3.6 365-day periodicity

We observe a transient yearly signal in X and Z CHAMP orbit-averaged data, even after removing an averaged contribution along the Z-GSM direction, which induces a yearly signal when transformed to SM frame. This contribution is visible mainly from 2001 to 2005 and was observed to reappear in both the components after 2009.

4 DISCUSSION

Figs 1 and 2 show the 1-, 14-, 27-, 90-, 210- and 365-day periodicities in the spectra of X-,Y- and Z-components. The appearance on these periodic signals, their LT dependencies and the origins of the associated signals are briefly discussed below.

The 1-day periodic signal clearly visible in X- and Y-residuals of the orbit-averaged data, is not visible in the Z-residuals. Although a simple explanation that the strength of this signal is too weak in this component is attractive, another hypothesis has our preference: the signal is from internal origin. A large-scale signal of internal origin, that is not constant along the longitude, appears in both X and Y SM-components with a strong 24 hr periodicity. The absence of signature in the Z-component is because, this axis is nearly aligned with the Earth's dipole axis. The averaging process we applied tends to weaken the contributions of the field of internal origin, but obviously, they are not completely removed from the time-series.

The signal with the 27-day periodicity is one of the most interesting signals appearing in these results. The signal was originally identified only in the east–west geocentric component (Lesur *et al.* 2005), around local midnight and for magnetically quiet times. Recently Lühr & Maus (2010) parametrized the signal along both X and Y SM directions. Here, we provide a clear evidence to show that the signal is present in all the three components. As described earlier, these signals have LT dependency, at least in the X- and Y-residuals. As the CHAMP satellite collects data only in a fairly small LT window for a given epoch and during that epoch, when the signal is present, it provides information on the LT dependence. A careful examination of the CWT results (Fig. 3) shows that the signal is dominant in X-component at dusk and dawn—that is, SM longitude $\simeq 100^\circ$ and 260°, whereas for Y-component, the preferred LT is after dusk—that is, SM longitudes $\simeq 220^\circ$. We note that, there may be a latitudinal component in this LT dependency, which could have been cancelled out by the averaging process. The mismatch between the local times of the observed signal in Lesur *et al.* (2005) and the present work, is likely to be due to the magnetic activity level: The CWT outputs are dominated by dawn-dusk signals present during magnetically active periods, whereas the quiet time signal is too weak to be seen. The LT dependency in the Z SM-component is not so obvious due to the added contributions of other sources. A detailed study does not indicate any preferred LT for this component. While the X- and Y-residuals show LT dependency for 27-day periodicity, the IMF-By data do not show any such dependency (Fig. 2). Therefore, to check whether or not the LT dependency of the signal is in any way influenced by the data window selection, we have imposed the same window to IMF-By data and performed CWT to that data. The results do not show any LT dependency on IMF-By data for this period. This reconfirms our observation that the intermittent temporal structure in all the residual scalogram plots is a pure LT dependent feature of 27-day periodicity. Vennerstrom *et al.* (2007) studied the influence of IMF-By and IMF-Bz on low latitude east–west perturbations and their dependence towards high latitude field aligned current (FAC) patterns, thus, suggesting a long-distance effect of high latitude FACs as a source to above mentioned perturbations. Our results support their hypothesis.

Owing to the narrow LT window of coverage by the CHAMP during a given epoch, it takes about 130.5 days to cover all LTs (this value varies by less than 0.5 day over the 10 years of CHAMP life). As a result, for an observer on the Earth, a LT dependent signal of 1-day period, actually corresponds to 130-day signal in the orbit-averaged CHAMP data. Thus, the drift of the orbital plane of CHAMP generates a 'frequency shift' effect (i.e. the frequency observed from CHAMP is not the true frequency as seen by an observer on Earth). Accordingly, we find a clear 130-day periodicity only in Z-component, albeit with small amplitudes after 2006. The lunar tidal signal, taking into account of the frequency shift, should appear with a 13.26 day periodicity, as observed on the day side in Park *et al.* (2012). We have observed some features at this frequency in the CWT spectra of CHAMP data but they do not present a clear distinctive pattern.

The signal with 210-day periodicity is conspicuously visible in the Y SM-component. To the authors' knowledge, there are only a very few reports of signals with frequency around 210-day periodicity. Fig. 4 distinctly shows the powers of 210- and 180-day signals that are extracted from the wavelet spectra of CHAMP Y-residuals, with 210-day signal being stronger than 180-day signal. It is also seen in Fig. 4 that, the 210-day signal appears to be periodic, in which the amplitudes of its peaks gradually decrease with time. The 180-day signal however does not exhibit such a periodic nature, though its amplitudes decrease gradually with time. A link to the solar activity is possible for such a phenomenon to occur but it is not tested for in the present study. Perhaps, longer data records (such as Swarm) are needed to have a better understanding of the evolution of the signal's strength with time. Due to the close proximity of 210- and 180-day periodicities and to further confirm that the coefficients related to these two periodicities are distinct, we have applied Morlet wavelet to a mixture of two synthetic signals with 210- and 180-day periodicities and a 10 per cent Gaussian

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noise added. The CWT spectra shows a clear distinction between these two closely spaced signals even with and without the added Gaussian noise. This qualitative test clearly suggests that the observed 210- and 180-day signals in the high quality CHAMP data are distinct and that there is no overlap between them in their time evolution. Further data analysis is warranted to identify the significance of this periodic signal in delineating the morphology of the external current system.

Although a stable field along Z-GSM direction, which induces annual signal when transformed to SM frame, was removed from the orbit-averaged CHAMP data, we still have observed some features with 365-day periodicity in the X-component, during the solar active period (between 2001 and 2005) (Fig. 2). This could probably be due to phase and amplitude differences between the 365-day signal in the X-component and the annual signal transformed in the SM frame.

Electromagnetic induction studies with satellite magnetic data may ultimately provide important new constraints on the electrical conductivity of Earth's mantle. Balasis *et al.* (2004) showed that, estimates of electromagnetic induction transfer functions obtained from CHAMP data under the traditional assumption of a magnetospheric symmetric ring current source have biases, that depend systematically on LT. Later Balasis & Egbert (2006) provided further evidence for non-axisymmetric magnetospheric source signatures from ground observatory data. In concurrent with their observation, the present study also indicates a local time dependency for signals with the 27-day periodicity and thus suggests that a purely zonal source model may be inadequate.

Wavelet analysis has provided valuable information on the fields generated in the ionosphere, magnetosphere and by field aligned currents and also on the LT dependency feature of 27-day variation. We expect that a similar analysis of the data acquired by three satellites of the forthcoming ESA Swarm mission will further confirm our observations. However, the results presented in this study call for a revision of the external field parametrization in magnetic field models in order to extract the best possible models of the core and lithospheric fields from Swarm data. We recommend that, such a parametrization could be based on the observed periodicities, probably accounting for the variation of the signal amplitude with time.

Data from the forthcoming multi-satellite multi-instrument Swarm mission are expected to advance geomagnetic field models and shed light on the electrical conductivity of Earth's mantle. A precise determination of external source effects together with the continuous flow of Swarm data are necessary to achieve these objectives.

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