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On the frequency spectra of the core magnetic field Gauss coefficients

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ABSTRACT

From monthly mean observatory data spanning 1957–2014, geomagnetic field secular variation values were calculated by annual differences. Estimates of the spherical harmonic Gauss coefficients of the core field secular variation were then derived by applying a correlation based modelling. Finally, a Fourier transform was applied to the time series of the Gauss coefficients. This process led to reliable temporal spectra of the Gauss coefficients up to spherical harmonic degree 5 or 6, and down to periods as short as 1 or 2 years depending on the coefficient. We observed that a k^{-2} slope, where k is the frequency, is an acceptable approximation for these spectra, with possibly an exception for the dipole field. The monthly estimates of the core field secular variation at the observatory sites also show that large and rapid variations of the latter happen. This is an indication that geomagnetic jerks are frequent phenomena and that significant secular variation signals at short time scales – i.e. less than 2 years, could still be extracted from data to reveal an unexplored part of the core dynamics.

1. Introduction

Geomagnetic field models have drastically improved over the last decade because of the availability of high quality satellite data. These models generally include sources of internal and external origins, but focus on the internal contributions. The spatial resolution of the contributions internal to the Earth now reaches Spherical Harmonic (SH) degrees as large as 120 or 130, in satellite-based models (e.g. Sabaka et al., 2015). This is much higher than the core field resolution that is limited to SH degree 13 or 14 due to the dominating lithospheric field at shorter wavelengths. It is unlikely that we can overcome this limitation without strong a priori information on the lithosphere. The situation is different for the temporal resolution that is limited to several years even for the very first SH degrees of the models. This is mainly due to difficulties in separating fields of internal and external origins – see e.g. Finlay et al. (2016). If we manage to circumvent these difficulties, induction effects in the conducting mantle should eventually limit the core field temporal resolution. We are very far from reaching this latter limit that we expect to be around few months (Jault, 2015). Signals generated in the core at short time scales – e.g. period of a year or less, are still to be revealed and may give new insight on the Earth core dynamics.

Core field models derived from satellite and observatory data are typically parameterised in time using B-splines (e.g. Olsen et al., 2006; Lesur et al., 2008; Lesur et al., 2010b; Lesur et al., 2015; Sabaka et al., 2015; Hamilton et al., 2015; Finlay et al., 2016), less often using polynomial expressions (e.g. Maus et al., 2006; Chulliat and Maus, 2014). To separate well internal and external contributions to the geomagnetic field the models are smoothed (or under-parametrised) in time, but this smoothing process leads to several difficulties. In particular it has been shown (Lesur et al., 2010a) that the resulting models have associated secular variations and accelerations that are not compatible with temporal variations due to advection processes in the core. Furthermore, separation of internal and external signals is achieved only if core field signals are over-smoothed. To model core field signals at short time scales, it is necessary to describe more precisely the external fields and also to give more realistic information on the core field temporal behaviour. In their widely used model COV-OBS, Gillet et al. (2013) propose to use a different type of a priori information for the core field. They hypothesise that Gauss coefficients behave like random variables that evolve in time following a linear stochastic process: an AR2 process. The process is tuned by assuming that the temporal spectra for the Gauss coefficients scale like k^{-4} where k is the frequency. This hypothesis is of course compatible with the spectrum of the observed magnetic field at the Earth surface that also behaves like a power law with a slope close to −4 (De Santis et al., 2003). However, the reverse

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is not necessarily true: the observed field may have a spectrum with a power-law of slope -4 whereas Gauss coefficients have a different behaviour. The hypothesis made by Gillet et al. (2013), therefore needs to be tested.

A first step in this direction has been made in Bouligand et al. (2016) where the spectra of Gauss coefficients obtained through rescaled numerical dynamo experiments are studied. Results are in line with the hypothesis made in Gillet et al. (2013): an AR2 process is a good description of the Gauss coefficient temporal behaviours and the coefficient spectra behave like k^{-4} for periods ranging from one year to 100 or 1000 years. This holds for all coefficients including the dipole field. However, despite the progress made in dynamo simulations, the parameter ranges in which these dynamos operate are not yet in the range of true Earth parameters (see Christensen and Wicht (2007) for a review and Aubert et al. (2017), for recent advances). It follows that approximating Gauss coefficient spectra with a power law of slope -4, is still questionable for the Earth on annual, decadal, and possibly centennial time scales. The goal of this paper is to verify this point.

We proceed by estimating Gauss coefficients for the Secular Variation (SV) using a correlation based modelling approach (Holschneider et al., 2016) and observatory data. The correlation based modelling is nothing else than a least-squares fit to the data of a heavily under-determined model where *a priori* information is provided through covariance matrices. In this application, this information reduces to the amplitudes and slopes of the Lowes-Mauersberger spectra of the modelled contributions to the magnetic field. This allows for a separation of internal and external signals that may not be perfect, but is better than what is achieved by using an SH decomposition alone. The key point here is that we are not using smoothing norms in time to separate external and internal fields as it is often the case in magnetic field modelling processes. As we are dealing with SV coefficients, we expect them to evolve in time in a similar way as a stochastic AR1 process. We consider two different time scales to check that this is not influencing our results. The derived time series of SV harmonic coefficients are then analysed through a Fourier transform to estimate the spectral content of their temporal variability.

The data set we used is made of monthly estimates of the SV derived from observatory data. This is described in details in the next section. In the third section we briefly described the correlation based modelling (Holschneider et al., 2016) and provide all necessary information for the model we used. We also shortly describe the way the Fourier transform is applied on the model. Results are presented in the fourth section and discussed in the final section.

2. Data

The data set is compiled from all available observatory hourly or monthly means generally provided by the World Data Centre (WDC) Edinburgh. We choose the starting epoch 1957, as the number of geomagnetic observations significantly increased during that year.

Following Wardinski and Holme (2006), monthly means are computed from hourly means when the latter are available, and secular variation estimates are computed by annual differences – e.g. for monthly means of the northward component

$$dX/dt|_t = X(t+6) - X(t-6), \tag{1}$$

where the time t is given in months. For some observatories, at early epochs, only annual mean data are available. In that case observatory annual means are treated using:

$$dX/dt|_{t+1/2} = X(t) - X(t-1), \tag{2}$$

where the time t is, in that case, in years. In all cases, known baseline jumps and discontinuities are corrected for.

This way of preparing the data set has a strong effect on the different signals contributing to the geomagnetic field. Computing monthly means smooth out contributions from high frequency signals and also, most of the contribution from induced fields. Further, taking annual differences significantly reduces the contributions of large-scale external fields in the data. That occurs because they usually present strong annual periodicities. Of course, non periodic external signals still contribute to the data. However, the main advantage in working with SV data, is that biases introduced in magnetic field components by the local lithospheric field, are removed.

No further processes are applied to the data set to remove contributions from external fields and/or their induced counterparts, since we expect our modelling scheme to separate the sources reasonably well. Nonetheless, to efficiently use the data set in a global modelling approach, the data have to be reoriented in the geocentric spherical North, East and vertical down directions (X, Y, Z directions), as observatory data are usually released in their geodetic local North East and vertical down directions.

There are in total 323 observatory sites spread over all continents (see Fig. 1). Not all observatories have a time series covering the full time span (see Fig. 2) and early data are concentrated in the Northern hemisphere. We are working with observatories that are necessarily situated on continents or islands. Therefore, oceanic areas are poorly sampled. This is mainly the case of the Eastern part of the Pacific Ocean, where modelled SV usually takes unrealistic values if appropriate constraints are not applied to the model.

Towards the end of the 1950s observatory data were recorded on photographic paper and had a poor temporal resolution. This was still the case for some observatories at the beginning of the 90's. However, the temporal resolution was by far good enough for monthly averages. Observatory data were digitised starting from the end of the 1970's but this did not change immediately the overall data quality. Yet, the quality and resolution of observatory data constantly improved from the 1980's until now. Temperature control and stability of the baseline remain difficult issues for observatory operations. Because absolute data have still to be collected by a trained observer, they must be located in vicinity of inhabited area, and anthropogenic noise affect most of the present observatory data, even if this noise remains often under the nT level. Finally, observatory data always carry natural signals associated with the direct environment and geology of the local area. Signal from oceanic tides and waves have been identified in some observatories – e.g. Love and Rigler (2014) and Manoj et al. (2011). Temperature variations, storms and electric activities produce also observable signals. These signals are poorly understood and are often considered as noise in global scale studies. Overall, it is extremely difficult to define and estimate this noise level in observatory data. We roughly estimate that the noise is normally distributed with a standard deviation (σ) of the order of 4 nT/y. We also assume that errors are de-correlated between observatories (which may not be the case when data noises are of natural origins), and that at one observatory site errors are de-correlated between orthogonal directions. This latter point is clearly a gross approximation but that cannot be avoided without precise information for each of the observatory site.

3. Theory

Correlation based modelling has been described in details by Holschneider et al. (2016). The main modelling assumption is that a noise free data value d_i is a random variable, normally distributed, with a mean $\bar{d}_i$ and a variance $\sigma^2_{d_i}$, i.e. $d_i \in \mathcal{N}(\bar{d}_i, \sigma^2_{d_i})$.

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