



Extracting planetary waves from geomagnetic time series using Empirical Mode Decomposition



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ABSTRACT

Empirical Mode Decomposition is presented as an alternative to traditional analysis methods to decompose geomagnetic time series into spectral components. Important comments on the algorithm and its variations will be given. Using this technique, planetary wave modes of 5-, 10-, and 16-day mean periods can be extracted from magnetic field components of three different stations in Germany. In a second step, the amplitude modulation functions of these wave modes can be shown to contain significant contribution from solar cycle variation through correlation with smoothed sunspot numbers. Additionally, the data indicate connections with geomagnetic jerk occurrences, supported by a second set of data providing reconstructed near-Earth magnetic field for 150 years. Usually attributed to internal dynamo processes within the Earth's outer core, the question of who is impacting whom will be briefly discussed here.

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1. Introduction

Planetary waves, also known as free, large-scale Rossby waves, are motions of the neutral gas in the Earth's atmosphere. Their theoretical prototype can be shown to be the solution of the set of equations describing isothermal atmospheres (Hirota and Hirooka, 1984; Hirooka and Hirota, 1985; Salby, 1984). It has been previously suggested that the observed atmospheric oscillations have an influence on geomagnetic variations due to a resulting dynamo action in the E-layer of the ionosphere (Forbes and Leveroni, 1992; Parish et al., 1994). Kohsiek et al. (1995) characterize their effect by three essential factors: 1. the ionization of the upper atmosphere (resulting from UV and X-ray radiation from the sun); 2. wind systems; 3. the permanent geomagnetic field.

Traditionally, evidence for the presence of planetary wave modes in geomagnetic time series is found using power spectral density estimates. The three most prominent modes, commonly referred to as 5-day, 10-day, and 16-day wave, feature approximate periods of $T \approx 4.5$ –6.2 days, $T \approx 7.5$ –12 days, and $T \approx 11$ –21 days, respectively (Salby, 1984). As conventional Fourier analysis is constrained to stationary data and linear processes with harmonic basis functions, the application of newer methods can provide

additional insight in the characteristics of planetary wave modes. Jarvis (2006) has used Short-Time Fourier Transform and Wavelet Transform to detect planetary wave modes. Here, we suggest Empirical Mode Decomposition (EMD), a spectral decomposition method working in the time domain, serving as a tool to extract these modes from geomagnetic variations and characterize their modulation. This technique has already been shown to be successful: Coughlin and Tung (2004) have used EMD to extract the 11-year solar cycle from stratospheric data, Roberts et al. (2007) extracted 60-year periodicities from length of day observations, Jackson and Mound (2010) found evidence for persistent internal time scales due to the outer core dynamo in geomagnetic data, Panovska et al. (2013) have used EMD and other techniques to search for periodicities of up to several thousands of years in Holocene sediment magnetic records.

Despite proving to be an effective algorithm, there are certain issues one needs to be aware of while using Empirical Mode Decomposition. In the present work we will discuss some of these before we employ EMD to extract and characterize planetary wave modes in geomagnetic time series. The paper is organized as follows: Section 2 gives a brief overview of the data used for the analysis. Section 3 will introduce Empirical Mode Decomposition as a procedure, and discuss some of the related difficulties. Section 4 will consider the extraction and characterization of planetary wave modes. Finally, discussion and outlook will be given in

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Section 5.

2. Data and preprocessing

With planetary wave modes being very pronounced in mid-latitudes, geomagnetic time series from three different stations in Germany are used. The three observatories are located in Niemegk (NGK), Wingst (WNG), and Fürstfeldbruck (FUR). An overview is given in Table 1. Following the study of Kohsiek et al. (1995) the aim is to show that EMD can provide similar results. In a later study, globally distributed data should be analyzed as well. The original time series feature hourly values of X-, Y-, and Z-components of the geomagnetic field. In a first step, these data are reduced to daily means. Following traditional suggestions, the data are then interpolated linearly when there are missing values (Kohsiek et al., 1995). Unfortunately, all records contain significant gaps of up to a few years in length (e.g., during World War 2 for NGK data). Therefore, it is not possible to use the full-length data for the analysis. Although EMD itself does not appear to be highly susceptible to non-equidistant sampling, formal frequency and period estimation is. As a consequence, the intervals that can be used are reduced to 1947/07/29–2013/12/31 (NGK), 1968/09/01–2012/12/31 (WNG), and 1946/08/02–2011/12/31 (FUR). From these intervals H-, D-, I-, and Z-components of the magnetic field as defined in Finlay et al. (2010) will be computed to be used in the analysis.

3. Empirical Mode Decomposition

Empirical Mode Decomposition has been introduced by Huang et al. (1998) as an effective algorithm to decompose time series into the so-called Intrinsic Mode Functions (IMFs, here referred to as “modes” to avoid any connotation with the interplanetary magnetic field). These modes form a (quasi-)orthogonal¹ set of basis functions that is derived directly from the original data without *a priori* assumptions about their nature. Besides orthogonality of the total set of basis functions, each mode is required to meet two extra conditions: First, the number of extreme values and zero crossings differ at most by one. Second, the “local mean” value of the mode is zero (Huang et al., 1998).

3.1. Fundamentals and spectral analysis

The basic algorithm of EMD can be described as follows:

1. Start with a discrete time series $x(t)$ with sampling period T_s .
2. Compute all maximum (minimum) values of $x(t)$, perform cubic spline interpolation, e_{\max} (e_{\min}), for these values.
3. Estimate the local mean of the time series as $m(t) = \frac{1}{2}(e_{\max} + e_{\min})$.
4. Subtract $m(t)$ from $x(t)$ and repeat the process with the resulting time series, beginning from Step 2, until a stopping criterion is reached.
5. When the stopping criterion is met, the first mode, $C_1(t)$, is found. Subtract this mode from the original signal and repeat the whole process for the residual.
6. The procedure can be stopped when the signal does not contain enough extreme values to perform interpolation. This residual can be regarded as the global trend, $R(t)$, of the time series.

¹ The term “quasi-orthogonal” refers to orthogonality in a numerical sense. No mathematical theory has been derived for EMD to this day (Deléclle et al., 2005).

Table 1

Information on the observatories.

| Station | Location | Time interval |
|---------|------------------|---------------|
| NGK | 52.08°N, 12.70°E | 1890–2013 |
| WNG | 53.75°N, 9.07°E | 1943–2011 |
| FUR | 48.17°N, 11.28°E | 1940–2011 |

By definition of the procedure, the original time series can be re-presented as

$$x(t) = \sum_{i=1}^n C_i(t) + R(t), \quad (1)$$

with n being the number of extracted basis functions.

EMD defines oscillations as the succession of extreme values and, consequently, permits modulation in its modes. It is therefore possible to perform time-dependent frequency and amplitude analysis. As suggested by Huang et al. (1998) this can be done using Hilbert analysis and transforming the independent modes into analytical signals. An analytical signal, $z(t)$, can be defined as

$$z(t) = x(t) + iy(t) = x(t) + i\mathcal{H}\{x(t)\}, \quad (2)$$

with $\mathcal{H}\{x(t)\}$ being the discrete Hilbert transform of $x(t)$ (Farnbach, 1975; Glassmeier, 1980). Using the amplitude and phase functions,

$$A(t) = \sqrt{x^2(t) + y^2(t)}, \quad (3)$$

$$\Phi(t) = \arctan \frac{y(t)}{x(t)}, \quad (4)$$

and the instantaneous frequency function

$$\omega(t) = \frac{d}{dt}\Phi(t), \quad (5)$$

the original time series can be represented as

$$x(t) = \sum_{i=1}^n A_i(t) \exp\left(i \int \omega_i(t) dt\right). \quad (6)$$

The decomposition performed by the EMD algorithm can therefore be regarded as a generalization of the traditional Fourier analysis. Still, Empirical Mode Decomposition lacks a theoretical basis (Deléclle et al., 2005).

3.2. Algorithmic obstacles

There are two main issues to be addressed when applying Empirical Mode Decomposition: First, the implementation of boundary conditions (or boundary extension), and second, the selection of an appropriate stopping criterion. Several different versions of boundary conditions and stopping criteria have been developed in the past. While all different methods do perform well (under certain conditions), the overall decompositions are sensitive to the choice of algorithmic variations. Unfortunately, few working groups mention their specific method in their publications. In order to be able to understand and reproduce results, it is yet absolutely necessary to reveal both stopping criterion and boundary extension method to the interested reader. In the present work, the amplitude ratio stopping criterion proposed by Rilling et al. (2003) is implemented using the default set of threshold values. The boundary extension method is based on linear extrapolation as suggested by Wu and Huang (2009).

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