Physics of the Earth and Planetary Interiors 270 (2017) 128–142

Contents lists available at ScienceDirect

Physics of the Earth and Planetary Interiors

journal homepage: www.elsevier.com/locate/pepi

Detection of secular acceleration pulses from magnetic observatory data

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ARTICLE INFO

Article history:
Received 30 March 2017
Received in revised form 28 June 2017
Accepted 18 July 2017
Available online 19 July 2017

Keywords:
Geomagnetic secular acceleration
Core magnetic field
Geomagnetic jerks
Magnetic observatories
Pattern recognition
Time series smoothing

ABSTRACT

Geomagnetic secular variation (SV) models for the epochs before the space era are based on magnetic observatory data, which represent relatively rough and noisy time series due to magnetic storms, anthropogenic spikes and gaps. These models are often strongly regularized in time, so that fast variations in the SV are smoothed out. However, recent studies show that at least some of the geomagnetic jerks observed at the Earth's surface emanate from increasing and decreasing phases of secular acceleration (SA) pulses at the core surface. The latter ones are direct manifestation of the dynamic processes taking place in the liquid core. They were first detected from satellite data, which are both of higher quality and more homogeneous in terms of geographical coverage than ground data. Herein we attempt to carry out similar studies based on observatory data available for a longer period. The proposed method of SV modeling and recognition of SA pulses relies on a new technique of processing time series based on fuzzy mathematics. Comparison with the SV modeling results derived from satellite data shows their high conformity with the proposed method. Stability and reliability of the SA pulse recognition are demonstrated by the examples of well-studied SA pulses in 2006, 2009 and 2012. Moreover, several new SA pulses around 1996, 1999, 2002 and 2014 are discovered as a result of the new approach application to multi-observatory data analysis. The latter provides a basis for applying the method to older historical data and investigate SA pulses and geomagnetic jerks further back in time.

1. Introduction

Variations of the Earth's main magnetic field (EMMF) at the Earth's surface and above encompass time scales from typically one year to millions of years. These variations include various manifestations of the geomagnetic secular variation (SV), such as the westward drift, the gradual decay of the geomagnetic dipole, the enlargement of the abnormally low intensity area in the South Atlantic region and the North magnetic pole drift. The SV is generated by convective flows, magnetohydrodynamic waves and diffusion processes in the Earth's outer core (e.g., (Finlay et al., 2010)).

On shorter time intervals, up to ten years, less evident SV variations can be detected by calculating the second time derivative of the field, i.e. the secular acceleration (SA). Sudden changes of SA polarity happening within a year or so can be seen in observatory data and models derived from observatory and satellite data. Such events, called geomagnetic jerks, take place at the junction of two time intervals characterized by practically linear change of SV (e.g., Mandea et al., 2010). Despite extensive studies of geomagnetic jerks over the past 30 years (see, e.g., Brown et al., 2013 for a recent compilation), their origin is still unknown. Jerks can be both regional and global in their spatial extent, and the time shift between manifestations at different observatories can reach up to 3 years. Recent geomagnetic jerks were detected in 2003 (Olsen and Mandea, 2007), 2007 (Chulliat et al., 2010; Kotze, 2011), 2011 (Chulliat and Maus, 2014) and 2014 (Torta et al., 2015).

One of the ways to investigate outer core dynamics is to construct time variant, spherical harmonic expansions of the EMMF using observations obtained at or above the Earth's surface. Since 2000, almost continuous, low-Earth orbit satellite observations of the Earth's magnetic field (e.g., Chulliat et al., 2017) have made it possible to build spherical harmonic models describing the time-varying part of the EMMF at much higher resolution (e.g., Finlay et al., 2016). Assuming the mantle is an electrical insulator, these models enable charting the SV and SA not only at the Earth's surface, but also at the core-mantle boundary (CMB) (e.g., Bloxham and Gubbins, 1985). However, downward continuation of the SA is only possible for models derived from recent, high accuracy

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http://dx.doi.org/10.1016/j.pepi.2017.07.005
0031-9201/

satellite observations, providing a geographically homogeneous coverage.

Recently, a new way to look at geomagnetic jerks has emerged, based on the analysis of satellite-based spherical harmonic models of the SA. Chulliat et al. (2010) showed that the global power at the CMB of the SA peaked around 2006, i.e., between the 2003 and 2007 jerks, a phenomenon referred to as an SA pulse. Other, similar peaks were later found in 2009 (Chulliat and Maus, 2014) and 2012 (Chulliat et al., 2015; Finlay et al., 2016), between the 2007 and 2011 jerks, and the 2011 and 2014 jerks, respectively. Therefore, recent jerks appear to be Earth's surface manifestations of transitions between two successive pulses at the core surface, and the question of the origin of geomagnetic jerks has shifted to that of SA pulses. Chulliat et al. (2015) pointed out that the spatial patterns of the 2006, 2009 and 2012 pulses at the core-mantle boundary were anti-correlated from one pulse to the next, suggesting a quasi-periodicity of 6 years. They further discussed possible physical mechanisms in the Earth's core that could result in the observed SA pulses, including equatorial Rossby waves in a stratified layer at the top of the core. An outstanding question is whether this new way of looking at jerks also applies to earlier epochs: are the jerks prior to 2000 also occurring at the beginning and end of SA pulses? A related question is that of the periodicity of older SA pulses: does the recently observed quasi-periodicity of 6 years continue back in time?

To address these questions, we developed a new mathematical method that enables recognition of SA pulses using solely observatory data. This method relies on Gravitational Smoothing, a new technique of time series smoothing based on fuzzy mathematics (Agayan et al., 2010,2014; Gvishiani et al., 2011). It enables detection of SA pulses without having to invert for a global, time-varying spherical harmonic model. The method was applied to data from 56 observatories worldwide, recorded during 25 years. The satellite-inferred SA pulses of 2006, 2009 and 2012 were successfully recognized by the method, demonstrating its reliability. Moreover, four new SA pulses were detected in 1996, 1999, 2002 and 2014, each between a pair of successive geomagnetic jerks and each with an opposite polarity to that of the next pulse, thus extending to twenty years the validity of the observed jerk/pulse relationship and the 6-year periodicity of the pulse phenomenon.

2. Method

Below we give a description of the method that was applied to detect SA pulses using multi-observatory data. Since we are interested in extracting a signal of internal origin, we first select data as much as possible cleared from contamination by external fields and the influence of the solar activity. For this purpose, for each component and observatory we select primary data at night and at magnetically quiet times and calculate hourly means. We use the following specific criteria:

1. Local time from 22.00 until 5.00,
2. -20 nT $\le$ Dst $\le$ 20 nT,
3. Kp $\le$ 2o,

Where Dst is the disturbance storm time index calculated by the WDC for Geomagnetism, Kyoto (http://wdc.kugi.kyoto-u.ac.jp/dstdir/index.html) and Kp is the global storm index provided by the GFZ German Research Centre for Geosciences (http://www.gfz-potsdam.de/kp-index/). We denote by *G* a record resulting from this filtering. In the next step, for a given *G* time series, we calculate mean values within each local time interval, as defined by criterion 1 above, and denote the result as *GM*. Despite the data selection, *GM* records are still noisy and contaminated by variations of external origin, including periodic (seasonal) variation. This is illustrated in Fig. 1, where the *GM* record obtained from the *Y* component recorded at the Alibag (IAGA code ABG) observatory and *X* component recorded at the Belsk (IAGA code BEL) observatory are plotted.

Let us denote m_i the number of *GM* elements contained in the *i*-th month, and *GMM* a set of monthly mean values calculated from *GM* (see Fig. 1). We assign to each month a weight w_i, depending on the number of *GM* elements contained in it and defined as $w_i = m_i/n_i$, where n_i is a number of days in the *i*-th month. As a result, we get a regular weighted time series *GMM* with a 1/12 year step (further referred as 1-month sampling).

Gravitational smoothing (GrS) (Agayan et al., 2010,2014; Gvishiani et al., 2011) is a new time series smoothing technique, relying on discrete mathematics analysis (e.g., (Soloviev et al., 2009,2012a; Bogoutdinov et al., 2010; Agayan et al., 2016)) and fuzzy mathematics principles. The result comes from sequential formalization of the following conjunction:

$$("x^* \text{ is a smoothing of } y") \equiv ("x^* \text{ is smooth"}) \wedge ("x^* \text{ is an approximation of } y").$$

The first proposition is measured by a functional $C(x)$, such that the smoother the time series, the smaller $C(x)$. In the GrS algorithm, $C(x)$ is based upon the notion of gravitational continuity, which is a discrete interpretation of the mean-value theorem for classical continuity: if a function f is continuous at a point t^* then

$$\lim_{\delta\to 0}\frac{1}{2\delta}\int_{t^*-\delta}^{t^*+\delta} f(t)dt = f(t^*). \quad (1)$$

We use a fuzzy structure $\delta_{t^*}(t)$ as a substitute for the neighborhood of a point t^*. $\delta_{t^*}(t)$ is defined at each point t in the t^* neighborhood, and summation is substituted for integration. As a result, gravitational continuity of a time series x at any point t^* is expressed as

$$\frac{\sum_t \delta_{t^*}(t)x(t)}{\sum_t \delta_{t^*}(t)} = x(t^*). \quad (2)$$

$\delta_{t^*}(t)$ can be chosen in an arbitrary way, however in the present studies the construction used for $\delta_{t^*}(t)$ is

$$\delta_{t^*}(t) = 1 - \frac{|t-t^*|}{\max(t^*-a, b-t^*)+h}, \quad (3)$$

where $[a,b] \subset \mathbb{R}_h^+$ is the domain of x, $\mathbb{R}_h^+$ is a set of positive real numbers with discretization step h. As it is seen from the definition, $\delta_{t^*}(t)$ represents a membership function according to fuzzy set theory (Zadeh, 1965; Gvishiani and Dubois, 2002; Ross, 1995), which expresses the measure of vicinity of t to t^* in the interval [0, 1], and thus being referred as fuzzy structure.The second proposition is measured by a standard L^2 norm $Sc(x|y)$ giving the distance between time series x and y:

$$Sc(x|y) = \|x-y\|^2. \quad (4)$$

Functionals $C(x)$ and $Sc(x|y)$ are combined in a linear way with respective weights defined by a single parameter $\lambda = [0,1]$ into the following functional:

$$Sm_\lambda(x) = \lambda C(x) + (1-\lambda)Sc(x|y). \quad (5)$$

The minimum of $Sm_\lambda(x)$ is obtained for $x = x^*$. The input parameter λ determines how strongly the original time series y is smoothed by the GrS algorithm, from 0 (no smoothing) to 1 (constant output value). Lambda is chosen empirically so that the *GMM* variations of the period less than half a year are smoothed out (see Fig. 1). Such variations, which are present in monthly mean records, probably do not reflect the EMMF variability due to the low-pass filtering effect of the lower mantle, although the exact