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Key Points:
- Direct observations indicate a new geomagnetic jerk at 2014
- A global perspective is given by a new model which confirms the jerk
- IGRF-12 secular variation predictions might be poorer than expected

Supporting Information:
- Movie S1
- Movie S2
- Figures S1–S3

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Evidence for a new geomagnetic jerk in 2014

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Abstract The production of quasi-definitive data at Ebre observatory has enabled us to detect a new geomagnetic jerk in early 2014. This has been confirmed by analyzing data at several observatories in the European-African and Western Pacific-Australian sectors in the classical fashion of looking for the characteristic V shape of the geomagnetic secular variation trend. A global model produced with the latest available satellite and observatory data supports these findings, giving a global perspective on both the jerk and a related secular acceleration pulse at the core-mantle boundary. We conclude that the jerk was most visible in the Atlantic and European sectors.

1. Introduction

Since the end of the 1970's, following the works of *Courtillot et al*. [1978] and *Malin et al*. [1983], the geomagnetic community is concerned about the appearance of sudden and abrupt changes in the trend of the first derivative of the recorded field elements at geomagnetic observatories. This first derivative, also known as geomagnetic secular variation (SV), as the main field itself, originates from the dynamics of the self-sustained core dynamo and is observed on the Earth's surface after the filtering effect of the conductive mantle. Working in parallel, the French and British groups observed the same phenomenon (now accepted as the 1969 jerk), although the book in which the British group published their paper appeared later because of some editorial difficulties (D. R. Barraclough and J. O. Cardús, personal communications). While *Courtillot et al*. [1978] talked about a "geomagnetic secular variation impulse," *Malin et al*. [1983] coined the term geomagnetic jerk ("by loose analogy with mechanics, where the rate of change of acceleration is called *jerk*"). Since then, several other jerks have been detected. Those with the widest consensus have turned out to correspond to epochs around 1978, 1991, 1999, and 2003, while others have been identified after analyses on older magnetograms or models. For an extensive review of geomagnetic jerks, their nature, and the different ways to isolate them, we refer to *Mandea et al*. [2010], *Pinheiro et al*. [2011], or *Brown et al*. [2013]. The most recent ones have been those of 2007 [*Olsen et al*., 2009; *Chulliat et al*., 2010] and 2011 [*Chulliat and Maus*, 2014]. The most striking result of the last two cited works is that the most recent jerks appear to originate from a succession of core field acceleration pulses (i.e., maxima of the second derivative of the field) occurring in Western Africa-South Atlantic Ocean and in South-western Indian Ocean.

Various more or less sophisticated methods, either applied to direct measurements or to the predictions given by geomagnetic models, have been used to detect and characterize geomagnetic jerks, such as those based on wavelet analysis [e.g., *Alexandrescu et al*., 1996], nonlinear chaotic analysis [*Qamili et al*., 2013], or Slepian functions [*Kim and von Frese*, 2013]. However, the original and most direct way to identify jerks is by looking for V- or Λ-shaped changes in the slope of the SV of one field component at geomagnetic observatories, after averaging either on an annual or a monthly basis in order to minimize the external field contribution. It was precisely for the sake of providing a means to promptly detect jerks, and thus to allow for a better forward extrapolation of models, that geomagnetic observatories were recently asked to generate Quasi-Definitive (QD) data through the INTERMAGNET facilities (www.intermagnet.org), i.e., data produced promptly by using provisional baselines, but still guaranteeing an accuracy close to that of definitive data [*Peltier and Chulliat*, 2010]. At the end of 2014 to early 2015, when preparing the last QD 1 min data files at Ebre geomagnetic observatory, some of us detected that such a clear change of slope started to appear in the corresponding monthly means. This was confirmed during the following months (thus discarding instrumental or external field effects) and also observed in several other observatories. This letter sets out our findings and is intended to advise the geomagnetic community about the evidence for a jerk around 2014.0.

Recent jerks have been found to occur at a regular rate (every 3–4 years) since 1999, suggesting that they are caused by some as-yet-unknown oscillatory phenomenon within the core. Finding a new jerk in 2014 further supports this hypothesis. The new jerk after the acceleration pulse in 2012.5 recently reported by *Chulliat et al*. [2015] and *Finlay et al*. [2015a] does not thus come as a surprise. Our results provide a compelling answer to the question of when would the next jerk occur/how long would the 2012.5 pulse last, and they do so only 1.5 year after the beginning of the jerk, thanks to the timeliness of observatory data delivery, the availability of high-quality *Swarm* satellite data, and the frequent updates of the CHAOS-5 core field model [*Finlay et al*., 2015a].

2. Data and Models Results

To look at the SV evolution during the last few years and analyze the signature of the latest jerks we relied on the geomagnetic observatory data provided by the World Monthly Means Database [*Chulliat and Telali*, 2007], while for the most recent data we resorted to the QD 1 min data files from INTERMAGNET and derived the corresponding monthly mean values. This allowed us to analyze observatory data until the end of June 2015. In order to remove as much external field signal as possible, in previous analyses of geomagnetic jerks it was common to compute monthly means only from nightside data and quiet time intervals [*Chulliat and Maus*, 2014; *Alken et al*., 2015] or by employing a dedicated two-step method [*Brown et al*., 2013]. However, here use has been made of the complete data set, because the changes on the trends are equally evident, and the extra time needed to select the data would have affected the promptness with which we wanted to present our results. As in *Chulliat et al*. [2010], to reduce external field influences such as the conspicuous seasonal variation, differences between monthly means were taken at times $t+6$ months and $t-6$ months, while those between annual means were taken at $t+1$ year and $t-1$ year. This limits the last epoch at which one can inspect those differences to 6 months/1 year before the last available data. Figure 1 depicts the trends of the first derivative of the X (north), Y (east) and Z (vertically downward) components of the field computed in this way at several observatories during the last two decades, with indication of the above-mentioned epochs at which evidence for geomagnetic jerks have been reported. The time variations of the SV computed from the observatory annual mean values and from the predictions given by the CHAOS-5 model are also plotted to better follow their trends. We show plots for Niemegk (NGK), Ebre (EBR), Tamanrasset (TAM), and Ascension Island (ASC) (ordered by latitude in the figure) in the European-Atlantic-African sector and for Guam (GUA) and Learmonth (LRM) in the Pacific and Australia-Indian Ocean sectors, respectively (at the bottom of Figure 1). We note that we have also observed similar results at several other observatories such as Chambon-La-Forêt, Kourou, MBour, and Honolulu, although we have not plotted the results for the sake of brevity.

Several facts are reflected in Figure 1. The first five are well known and confirmed by this study; the remaining two are new:

1. Jerks are not seen in all components at all observatories [e.g., *Mandea et al*., 2010]. However, except for ASC in the Z component, the 2014 jerk is rather clear in all of the inspected observatories and components of this study.
2. When attempting to isolate the genuine core signal, the least contaminated component from external fields at midlatitudes is the Y component [*Pinheiro et al*., 2011]. Monthly mean amplitude changes of the X component are noisier, because of the residual effect of the ring and the auroral currents. Noise also appears frequently in the Z component, because of the induction effects on islands, coasts, or resistive terrains. Mean trends in these latter two components are also affected by the latitudinal displacements of the auroral currents during severe storms. It is also evident that epochs close to a solar maximum are more contaminated from external effects than those corresponding to solar minima and that the last solar cycle (number 24) has been less active than the former ones.
3. Jerks are not globally simultaneous [e.g., *Brown et al*., 2013]. Epochs of geomagnetic jerks may vary as much as 1–2 years from one region to another.
4. Over the time interval shown, the changes of slope are clearest in the Atlantic-African region, where the SV is also the largest [*Chulliat et al*., 2010].
5. During the last two decades jerks correspond to a sort of oscillatory process in the SV behavior, with a semiperiod of 3–4 years [*Chulliat and Maus*, 2014].
6. In contrast with most of the previous jerks, the rate of change of the SV in Europe after the 2014 jerk has increased, making it closer to that experienced at the African-Atlantic observatories.

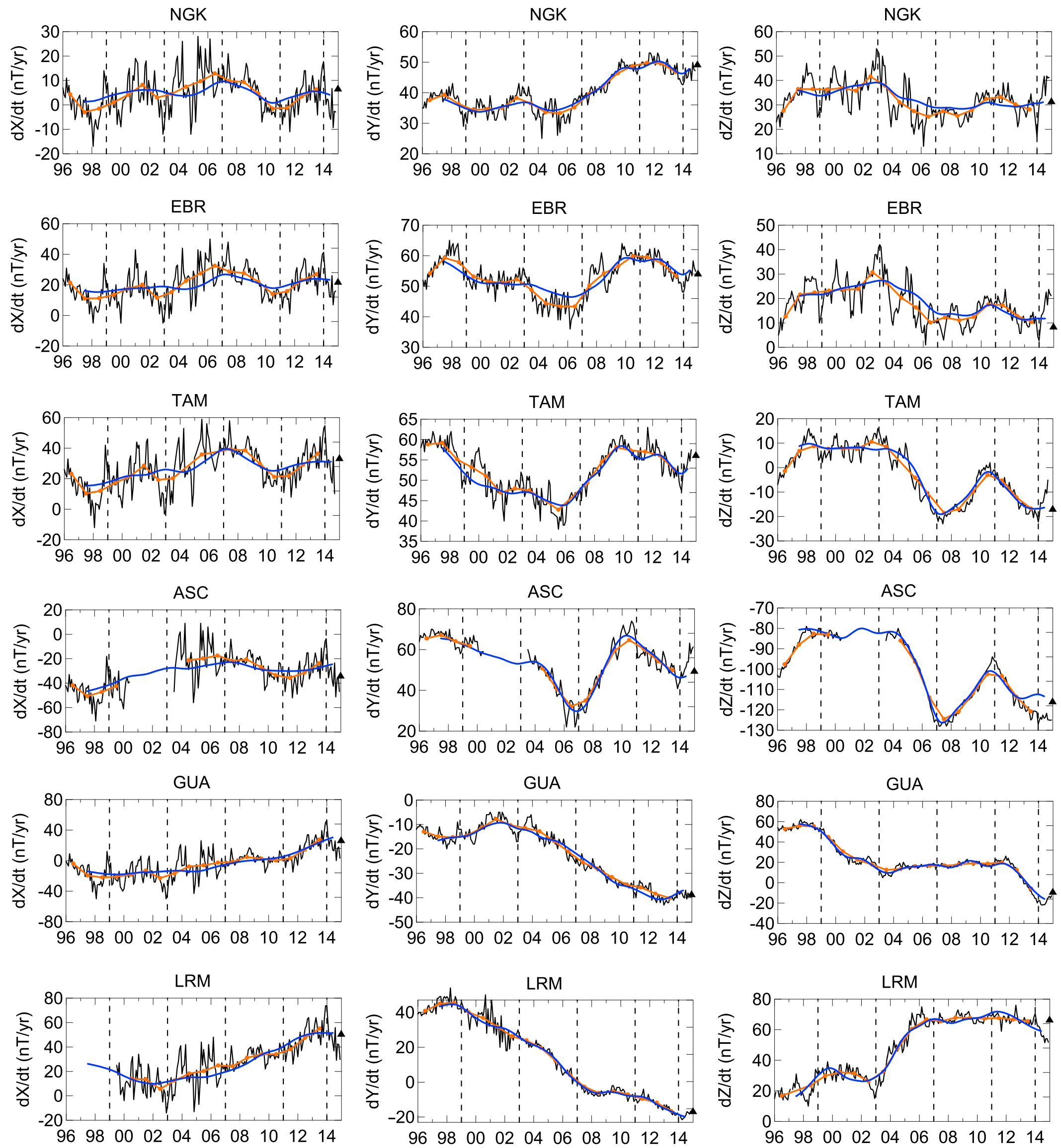

Figure 1. Observed SV computed as the differences of monthly means (black) and annual means (orange) at several observatories identified by their three-letter International Association of Geomagnetism and Aeronomy code. The SV calculated from the CHAOS-5 model is plotted in blue, and the SV at 2015.0 as given by the IGRF-12 is indicated by the black triangles. Dashed lines indicate the 2014.0 epoch and those of the formerly reported jerks. The labels in the horizontal axes represent the last two digits of the year.

7. As the occurrence of the jerk was very close to the epoch of the latest data available for the production of the model candidates to the new generation of the International Geomagnetic Reference Field (IGRF-12) [*Thébault et al.*, 2015], at least one of them (the CHAOS-5) and, in consequence, the IGRF-12 itself, does not extrapolate well the SV behavior from that epoch onward, especially for the *X* and *Z* components (the change of slope in 2014 for the *Y* component, on the contrary, is rather well captured).

Following the approach of *Chulliat et al*. [2010], we additionally investigated whether the evidence for the jerk in the observatories are also reflected in the synthesized values and maps of the acceleration changes from spherical harmonic (SH) models. As explained above, because of the lack of recent data, the IGRF-12 candidate models are not well suited for this purpose, so we needed to rely on a more recent model, which includes updated observatory and, especially, satellite data, in order to guarantee a global data coverage. For this purpose we analyzed an update of the CHAOS-5 model, CHAOS-5x_v3. Its characteristics are

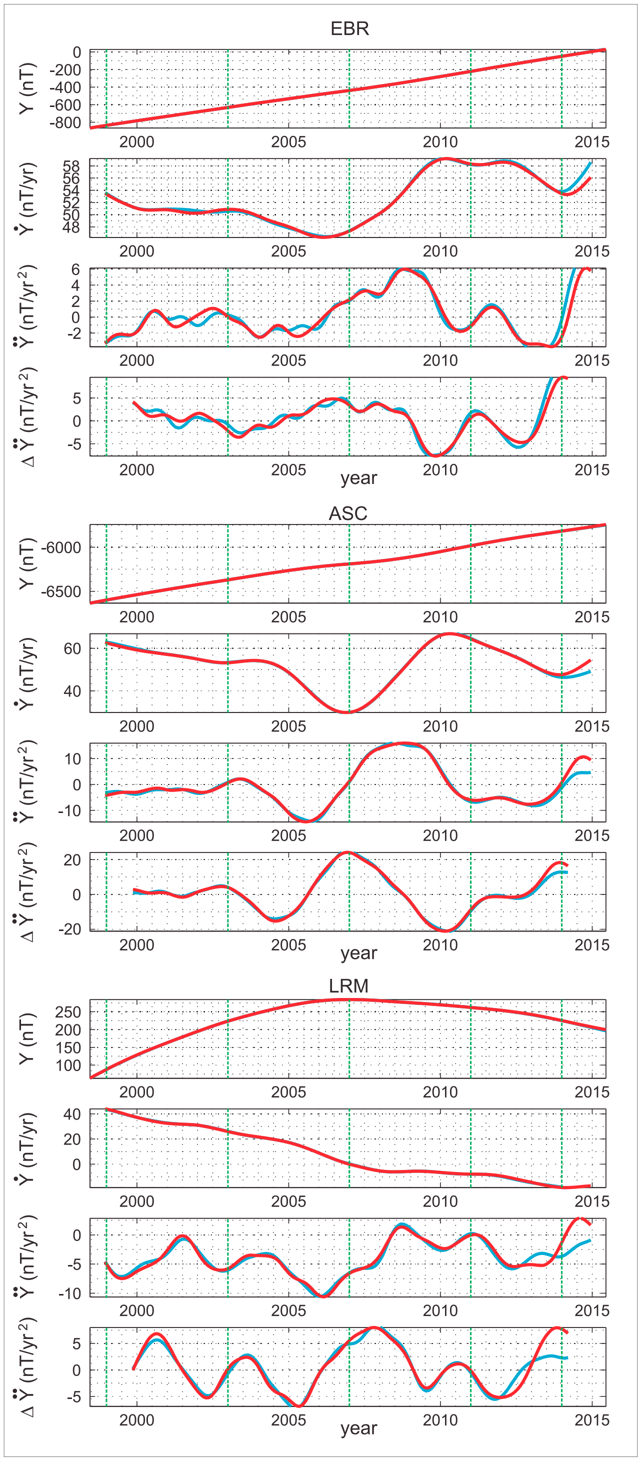

Figure 2. *Y* component of the geomagnetic field, and its first (SV) and second (SA) derivative, along with the SA changes (denoted as $\Delta\ddot{Y}$), which are thus proportional to the third derivative (see main text), at (top) EBR, (middle) ASC, and (bottom) LRM as synthesized from the CHAOS-5 (blue lines) and CHAOS-5x (red lines) models. Vertical green lines indicate the 2014.0 epoch and those of the formerly reported jerks.

essentially the same as those of CHAOS-5, but it was derived using data up to 2015.5, and additionally makes use of *Swarm* along-track and east-west field differences, which approximate field gradients [*Finlay et al.*, 2015b]. The (relatively minor) differences between CHAOS-5 and CHAOS-5x in earlier years are due to (i) the use of along-track scalar gradients from *Oersted* and CHAMP, and along-track vector gradients from CHAMP in CHAOS-5x, that were not used in CHAOS-5, and (ii) slight differences in the imposed regularization, partly due to different numbers of contributing data. CHAOS-5x_v3 is a provisional model, primarily designed to represent secular variation in 2014 and early 2015 better than CHAOS-5. Work on the method of incorporating satellite magnetic gradient estimates is ongoing and will be the subject of a future study.

Figure 2 shows the evolution of the *Y* component of the field, and its first (SV), second (known as secular acceleration (SA)), and third derivatives (evaluated using changes in the SA) in Europe, the South Atlantic, and Australia-Indian Ocean, represented by the locations of EBR, ASC, and LRM, respectively, using the predictions of the CHAOS-5 and CHAOS-5x models. A figure in the supporting information shows this at the locations of all the studied observatories and components (see Figure S1 in the supporting information). As previously, the SV at a given epoch was computed as the difference between the field 6 months after and 6 months before that epoch. SA was computed using the formula given by *Tozzi et al.* [2009], again with $t_{i+1} = t_i + 6$ months and $t_{i-1} = t_i - 6$ months. SA changes, in contrast, were taken as differences between times $t + 10$ months and $t - 10$ months, so as to, on one hand, provide smooth changes and, on the other hand, be able to compute them at least until the beginning of 2014. Again, these procedures progressively limit the epochs at which one can inspect each

Table 1. Jerk Amplitudes[a]

Observatory	Nominal Jerk 2007	Nominal Jerk 2011	Nominal Jerk 2014
NGK	4.6 (2006.0)	−6.2 (2011.8)	7.2 (2014.0)
EBR	5.6 (2006.4)	−6.7 (2011.0)	12.7 (2014.0)
TAM	8.2 (2005.7)	−6.8 (2009.5)	15.2 (2014.0)
ASC	23.4 (2006.9)	−19.5 (2012.0)	24.9 (2014.1)
GUA	-	-	4.7 (2013.2)
LRM	10.8 (2008.1)	-	10.6 (2014.3)

[a]The amplitudes (in nT/yr^2) correspond to the *Y* component. Positive amplitudes denote V shapes, while negative amplitudes denote Λ shapes of the SV trend. The hyphen symbol indicates that the jerk was not evident at that observatory. The dates of occurrence of each nominal jerk at each observatory are given parenthetically.

of the analyzed quantities. Thus, considering that CHAOS-5x is valid until 2015.5, SA changes can only be in this way computed until February 2014.

As is well known, "clean" jerks at a particular epoch ideally appear as a narrower or wider, taller or shorter, V or Λ in the first derivative, a step in the second derivative, and a Dirac delta function in the third derivative. However, models such as CHAOS based on high (sixth)-order spline basis functions will produce a continuous third derivative; i.e., they cannot formally produce delta impulses in the third time derivative but prominent (finite) peaks at most. A further problem is their imposed temporal regularization, which results in the model and its time derivatives (including the SA and third time derivative) being effectively smoothed in time by convolution with a filter function [*Gillet et al*., 2013]. The temporal smoothing time of the filter is longer at higher degrees; for example, *Olsen et al*. [2009] estimates smoothing times of approximately 6 months for degree 1, and 2 years for degree 5. As extensively discussed in the previous literature, some jerks reveal those nominal characteristics better than others, but what Figure 2 emphasizes is that the amplitude of this new jerk is at least of the same amplitude as the most prominent ones during the last 15 years and that it is certainly the clearest on the *Y* component in Europe. This fact is substantiated with the outstanding (with respect to previous years) peak in the magnitude of the SA changes of this component at EBR around 2014.0. Even if not so important in relative terms, this peak is also considerable in the *X* and *Y* components of ASC and in the *Y* component of LRM.

To better characterize the new jerk, we numerically compared it to the amplitudes of the 2007 and 2011 jerks. The determination of the jerk amplitudes at each observatory was made using the method proposed by *Pinheiro et al*. [2011], i.e., evaluating the SV slopes before and after the jerk and subtracting the former from the latter. Although conceptually simple, this method does have some difficulties—particularly, the choice of both the time window for the application of the method, and the jerk occurrence time, t_0. In that study most of the reported results were computed from annual means and the most reliable results were obtained when there was a sufficiently long "straight-line" segment on each side of the jerk (e.g., a 10 year window around 1969). However, the time window chosen for each jerk cannot contain data beyond the epoch of the neighboring jerks. When one lacks long straight segments on each side of the jerk as in our cases (recent jerks are close together, and the latest one is still relatively recent), uncertainties are obviously higher, but we believe that this procedure is still a reasonable way to compare the relative importance of each detected jerk. After a first visual inspection of the SV trends and jerks for each observatory in Figure 1, the values for the initial and final epochs of the time window were selected. Consecutive linear fits were then computed by varying the intersection time t_0, and the finally adopted value for this variable was selected according to the lowest misfit. An additional constraint was added to the independent terms of the two adjacent linear fits, so as to guarantee the continuity of the SV. This procedure was only applied to the *Y* component because, as stated, it is the "cleanest" component to detect jerks. The results are given in Table 1 which, despite the noted uncertainties of the method, emphasize both the relative importance of the 2014 jerk (especially in Europe) and the nonsimultaneity of the jerk occurrence times.

We also produced SA change maps for each component from October 1998 to February 2014 from CHAOS-5x, computed as above at every month using a Δt of 20 months. This illustrates the evolution of the global structure of the SA changes at the Earth's surface (see Movie S1 In the supporting information). Figure 3 shows the maps for 2014.0. Their patterns are coherent both with what is shown at the locations indicated

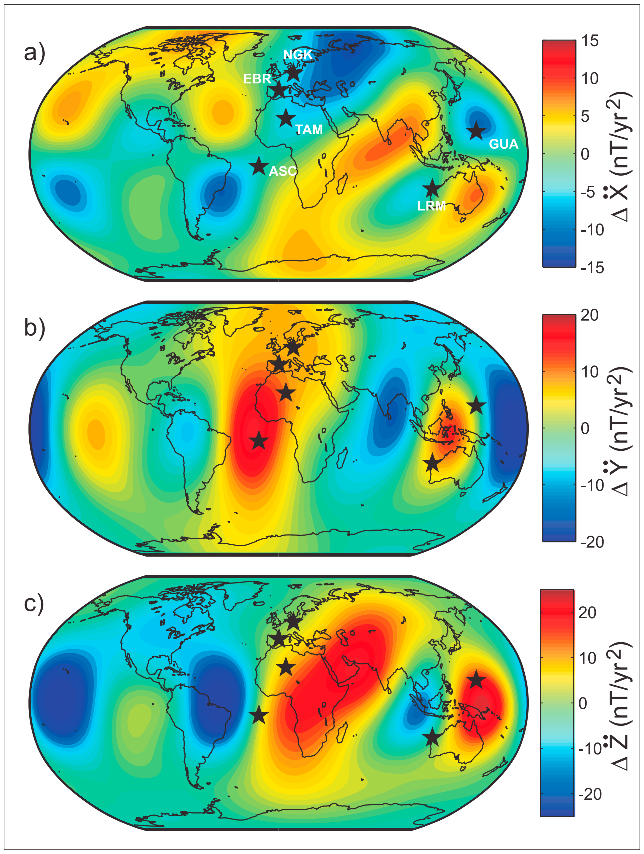

Figure 3. Global maps of the *X*, *Y*, and *Z* secular acceleration changes at 2014.0 at the Earth's surface obtained from the CHAOS-5x model. Note the location of the observatories where the changes have been inspected.

in the previous graphs for the same epoch and with the remarkable prominence of the peak in the magnitude of the *Y* SA change, which extends approximately along the Atlantic-westernmost African meridian. Another peak in the magnitude of the SA change just as prominent, but with opposite sign, is detected approximately along the opposite meridian (on the so-called perioecus), in the Pacific. An interesting observation, evident in the previous figures and table, is that no such large SA change was observed in the Pacific during previous jerks. The most outstanding patches in the *X* and *Z* SA changes appear, on the contrary, somewhat displaced toward the East, centered on the Northern Urals and on the Arabian Peninsula, respectively, with other significant patches centered on Sri Lanka and New Guinea, respectively, with their counterparts of opposite sign on the perioeci.

To confirm the widely accepted assumption that SA changes at the Earth's surface are the consequence of acceleration pulses at the core surface [*Chulliat et al*., 2010] and to see if consecutive geomagnetic jerks are coherent with the occurrence of those pulses at intermediate epochs, we considered maps of the acceleration at the core-mantle boundary (CMB) (see Movie S2). Figure S2 shows a sequence of these latest maps from January 2002 to January 2014, spaced every 1.5 years. It confirms the findings of *Chulliat et al*. [2010] and *Chulliat and Maus* [2014] that jerks emerge at intermediate epochs between acceleration pulses of the radial field at the CMB, suggesting that those pulses are the common cause of the geomagnetic jerks. Although their origin in the core is still uncertain [*Chulliat and Maus*, 2014], this series of events are predominantly manifested at low latitudes and they show an alternating polarity. Thus, in addition to the SA pulses in 2006 and 2009 discussed by *Chulliat and Maus* [2014], the results of this study confirm a new pulse in 2012–2013 [*Chulliat et al*., 2015; *Finlay et al*., 2015a]. Thus, the last two jerks, at 2011 and 2014, would have occurred as the ascending and descending phases of the intense acceleration detected by the CHAOS-5x model in 2012–2013. This latest SA pulse seems to correspond to a new manifestation of the sequence, which is repeated approximately every 3–4 years during the last 10–15 years. The occurrence of a new jerk after the 2012.5 pulse has thus not been a surprise, and the only real question was how long would that pulse last.

Acceleration pulses at the CMB must be coherent with the time variation of the acceleration power of the model. Following the analysis of *Chulliat et al*. [2010] and *Chulliat and Maus* [2014], we computed the time variation of the SA power of each spherical harmonic degree at the CMB from the coefficients of the CHAOS-5x model (Figure S3). Our result reflects again the oscillatory character of the intermediate-to-low degree SA behavior, with peaks approximately every 3 years during the last decade. Different harmonic modes peak simultaneously in the 2006.5 pulse, but some phase differences are seen in the following peaks, which might explain the noted lack of simultaneity of the majority of jerks at different regions. Another possible reason for the phase differences between the SA peaks could also be connected to the fact that the CHAOS-5 data set is not homogeneous, as there are no satellite vector measurements from 2010.5 (end of

CHAMP) to 2013.9 (beginning of *Swarm*). However, what is most evident is the noticeable amplitude of the peaks corresponding to $n = 5$ and 7 in the latest pulse in relation with previous SA pulses, which makes the 2014 jerk significant.

3. Conclusions

Although the geomagnetic secular variation is a phenomenon which has been generally conceived as unpredictable [e.g., *Malin*, 1985], various methods to forecast it have been attempted with greater and lesser degrees of success [*Whaler and Beggan*, 2015, and references therein]. Some are based on data assimilation techniques; others on being able to guess what would be both the relevant rapid physical processes of the core magneto-hydrodynamics and the electrical properties of the mantle, and to derive the appropriate equations that govern those processes. In any case, to succeed with these attempts, all of the prediction methods must rely on the availability of promptly provided definitive, or at least quasi-definitive, observational data. Recently, quasi-definitive data from observatories, and data from satellite missions such as *Swarm*, provide this possibility. However, by its nature, the advent of a geomagnetic jerk is the clearest obstacle to such predictions, and both the geomagnetic community and model users need to be aware of them.

It can take some months, even years, to ensure that a jerk has occurred. This is because other signals are involved in a geomagnetic measurement, and they are not easily separable (sometimes spatial and temporal wavelengths are mixed). But also simply because to draw the trend changes that uniquely characterize the jerk, the procedures used to provide numerical differentiations need data extending several months beyond the epoch of the jerk. Despite all this, we believe that there is sufficient evidence from the current data and models to confirm the occurrence of a new geomagnetic jerk around 2014.0. As with previous jerks in the last decade or so, this new 2014 jerk is especially evident in the *Y* component and in the Southern Atlantic-African region, but this time it further extends toward Europe and the North-Western Atlantic. A second, less extended but equally clear, patch in this component is detected in a region between Philippines and Australia. Symptoms of the jerk are also seen in the other components, although not always as clear and not exactly at the same epoch.

Results from the SH coefficients of a model produced with the latest available observatory and satellite data support a new characterization of 3 year sequence of alternating pulses in core field SA during the last decade. A new peak in the SA power is coherent with the occurrence of the new jerk at the Earth's surface. *Chulliat and Maus* [2014] suggest a wave motion within the core for the 3–4 year return period of the jerks now observed. If their theory is correct, it might provide an element of predictability of the geomagnetic SV.

Elucidating the cause of the reported jerk from the point of view of the source mechanisms in the core is intentionally beyond the scope of this work. Our purpose was that of pointing out some of its features, to emphasize the importance of providing quasi-definitive observatory data, and to note that in the case that the present SV persists, field predictions from IGRF-12 and related models might be poorer than expected in the upcoming years.

Acknowledgments

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