Investigation of a secular variation impulse using satellite data: The 2003 geomagnetic jerk

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Abstract

Observatory monthly means provide an excellent opportunity to study the temporal changes of the magnetic field at a given location. Unfortunately, the uneven distribution of the present observatory network makes it difficult to determine the global field change pattern. Recently, we have developed an approach to extract satellite monthly means at a regular network of “virtual observatories” at 400 km altitude, based on CHAMP magnetic measurements.

Using monthly means for 2001–2005 from those “virtual observatories” we investigate the space–time structure of the short-period variation of the Earth’s magnetic field by means of a Spherical Harmonic Expansion, followed by a separation into external (magnetospheric) and internal part. This allows, for the first time, to study the secular variation globally and directly from satellite magnetic data.

Analyzing the time series of the magnetic field at the “virtual observatories” as well as those of the spherical harmonic expansion coefficients, we detect a secular variation impulse (an abrupt jump in the second time derivative of the magnetic field) in the CHAMP satellite data during the first months of the year 2003. The jerk occurred simultaneously in the northern and southern hemispheres in a rather limited area near 90° E, with maximum jerk strength at about ±30° latitude, a region also characterized by a strong secular acceleration (second time derivative of the magnetic field). We show that the 2003 geomagnetic jerk is not worldwide in occurrence and that there is an evidence for this event in the length-of-day variation.

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1. Introduction

The main part of the Earth’s magnetic field is generated by a self-sustaining dynamo in the fluid outer core. The field is, however, not constant but changes with time, a phenomena denoted as “secular variation” (SV). Abrupt changes in the linear secular variation trend occur occasionally and have been named “geomagnetic jerks” or “secular variation impulses” (e.g. [1–3, and the references therein]). Despite efforts made during the last years in studying geomagnetic jerks, and some progress in understanding this phenomenon, some key features are still questionable.

Secular variation, and especially geomagnetic jerks, are traditionally studied using time series of the magnetic field recorded in geomagnetic ground observatories. The very uneven distribution of the observatory network...
hampers, however, investigations of the spatial distribution of jerks. Impressively progress in determining the spatial structure of the Earth’s magnetic field changes has been made by analyzing magnetic measurements taken by recent multi-year satellite missions Ørsted, CHAMP and SAC-C. However, no jerk has been so far noted over the time-interval for which satellite magnetic data are available. Moreover, the data time series have to cover several years in order to isolate the V-shape pattern in the first time derivative of the magnetic field, which indicates a geomagnetic jerk.

As an example of jerks observed by ground observatories, Fig. 1 shows the first time derivative, $dY/dt$, of the magnetic East component at the observatory Niemegk in Germany, computed as first differences of the monthly mean values. To remove an annual variation – caused by magnetospheric and ionospheric currents and their Earth-induced counterparts – a 12-month running mean has been applied to the first differences, as is common practice when studying jerks (e.g., [3]). This is equivalent to calculating the value at time $t$ as the difference between the values at time $t+6$ months and $t-6$ months, i.e. effectively the “running means” of differences do not imply any smoothing. Rather than showing the geographic East component, we plot the East component in a coordinate system that is aligned with the main field dipole axis, since that component is not contaminated by magnetospheric ring current contributions. The transformation from geographic to dipole components amounts at Niemegk to a rotation of the horizontal components by 18°, which significantly reduces the short-period scatter of the monthly mean values in the rotated East component. Clearly, this confirms the existence of magnetospheric contributions in observatory monthly mean values. The right panel of Fig. 1 is a magnification of the left panel, emphasizing the last 25 yr.

Predictions of various models of the Earth’s magnetic field are also plotted. Model $gufm1$ by Jackson et al. [4] is mainly derived from ground data and does not describe the fine-structure of the field changes, due to applied damping in time and space in order to allow for a field description back in time to 1590. The Comprehensive Model, $CM4$, by Sabaka et al. [5] spans more than 40 yr (1960–2002). Derived by a joint analysis of ground-based and satellite data, the prediction of this model is presented in both panels. Finally, the prediction of the recently derived satellite-only based $CHAOS$ model by Olsen et al. [6] is also shown. The last reported jerk occurred at the end of the XXth century [3], but visual inspection of $dY/dt$ at Niemegk suggests that there also may have been a jerk around 2003.

Interestingly, the occurrence of a jerk around 2003 is not only seen in the observatory data, but also in the $CHAOS$ model predictions. This model, derived from

![Fig. 1. First time derivative of the Y-component at Niemegk observatory (Germany). Predictions of the $gufm1$ model by Jackson et al. [4] is shown in green, of the $CM4$ model by Sabaka et al. [5] in blue, and of the $CHAOS$ model by Olsen et al. [6] in red.](image-url)
Orsted, CHAMP and SAC-C satellite magnetic data between March 1999 and December 2005, describes the secular variation of the core field up to spherical harmonic degree $n = 14$ by means of cubic $B$-splines with a knot separation of 1 yr. However, the second time derivative of the squared magnetic field, averaged over the Earth’s surface, has been minimized during the model estimation process, which is one of the reasons that the observed values in the right panel of Fig. 1 exceeds the variation predicted by the CHAOS model.

The event observed in Niemegk data and in the CHAOS model lead us to investigate in more detail the magnetic field variations around 2003. A jerk in 2003 would be the first time such a phenomenon appears during a period for which magnetic measurements from space are available. This is the motivation to directly analyze CHAMP magnetic data. Unfortunately, the available monthly series after the event is not long enough to use alternative analysis techniques (e.g., a wavelet method).

Recently, we developed an approach to derive satellite monthly means at “virtual observatories” at 400 km altitude from CHAMP magnetic measurements [7]. Comparing the virtual observatory monthly means with the corresponding ground observatory values we found a remarkably well correlated signal at time-scales of months to years. In the present paper we use this method to investigate the jerk around 2003.

When studying secular variation from satellite measurements, typically data during geomagnetic quiet times, defined by activity indices like Kp, are used. However, due to varying geomagnetic activity, the number of selected satellite data may vary substantially from year to year. 2003, the year for which we claim the occurrence of a jerk, was geomagnetically rather active, with only 27% of the Kp values satisfying Kp $\leq 2^\circ$. For all other years between 1997 and 2005 this percentage varies between 50% and 70%. Note that only data with Kp $\leq 2^\circ$ were used in the CHAOS model, and thus this model is based on less data for 2003, compared with the other years.

Ideally, a model should be derived from data that are equally distributed in space and time (or an appropriate weighting has to be applied). When constructing field models from ground observatory data (monthly or annual mean values), the year-to-year variability of geomagnetic activity is typically neglected, since monthly (annual) means are calculated by averaging over all days of a month (year). In addition, observatory data from all hours of the day (i.e. all local times) are used when deriving field models, while typically only quiet local night-time satellite data are chosen. Hence, there are considerable differences in the data selection when dealing with observatory, respectively satellite measurements. However, model features can only be regarded as robust if they are independent of the specific data selection.

In the present paper we therefore use two approaches for studying the recent secular variation. Besides interpreting the secular variation part of the CHAOS model derived from satellite data that have been selected according to geomagnetic activity and local time, we derived a field model based on “satellite monthly means”, thereby combining the advantages of ground observatory data (time series at a fixed location) with those of satellites (excellent global coverage). In addition to a visual inspection of time series of satellite monthly means at given positions (at a regular grid of “virtual observatories” in space) we perform a Spherical Harmonic Transformation, followed by a separation into internal, external (magnetospheric), and toroidal parts, and investigate the time change of the spherical harmonic expansion coefficients. Finally, we discuss the link between geomagnetic and geodetic data, by investigating the correlation between the 2003 jerk and special features in the length-of-day (LOD) variation as noted for previous events by Holme and de Viron [8].

2. Time series of satellite monthly mean values

Following Mandea and Olsen [7], we use CHAMP satellite magnetic vector measurements $X, Y, Z$ (1 Hz sampling rate) of the three field components $X$ (geographic North), $Y$ (geographic East), and $Z$ (vertical downward) for the years 2001–2005, from which we determine monthly mean values at a regular grid of “virtual observatories” at 400 km altitude (the mean CHAMP altitude). In order to make processing of the satellite data similar to the way observatory monthly means are derived, we use all CHAMP vector data (i.e. all local times, all geomagnetic activity conditions). Consequently, our data selection is different from that traditionally used when deriving field models from satellite data (where typically only quiet-time night data are used).

For deriving the monthly mean values, we calculate magnetic field residuals, $\Delta B = B_{\text{CHAMP}} - B_{\text{mod}}$, by subtracting a model field $B_{\text{mod}}$ from the CHAMP measurements $B_{\text{CHAMP}}$; as model field we take the static field (spherical harmonic degree $n \leq 20$) and the first time derivative ($n \leq 8$) of the CHAOS model by Olsen et al. [6].

Monthly mean values are derived from the field residuals, $\Delta B$, that are closer than 400 km to the “target point” (i.e. the position of the virtual observatory, located at 400 km altitude) during the month in consideration. In
doing so we assume that $\Delta \mathbf{B} = - \nabla V$ is a Laplacian potential field that varies linearly in spatial coordinates (i.e., the potential $V$ varies quadratically in space). This eliminates contributions from electrical currents at satellite altitude, for instance from field-aligned currents. Due to $\nabla^2 V = 0$, the potential $V$ of such a field is characterized by only 8 independent parameters:

$$V = v_x x + v_y y + v_z z + v_{xx} x^2 + v_{yy} y^2$$

$$- \left( (v_{xx} + v_{yy}) z^2 + v_y x y + v_x x z + v_{yz} y z \right)$$

where $x$, $y$, $z$ are local Cartesian coordinates of a frame that is centered at the target point, $x$ pointing towards geographic North, $z$ upward, and $y$ completing a right-handed coordinate system. Note that assuming an independent linear spatial dependence of each component of $\Delta \mathbf{B}$ requires 4 independent parameters per component, i.e. 12 parameters in total. Assumption of a Laplacian potential field reduces this number to 8 independent parameters, since the conditions $\text{div} \mathbf{B} = 0$ (1 scalar constraint) and $\text{curl} \mathbf{B} = 0$ (3 scalar constraints), i.e. 4 constraints in total, are used. The 8 parameters $(v_x, v_y, v_z, v_{xx}, v_{yy}, v_{yy}, v_{yz}, v_{yz})$ are estimated from the magnetic residuals $\Delta \mathbf{B}$ using iterative reweighted Least Squares (Huber weights with a tuning constant of 1.5, cf. Holland and Welsch [9]). The mean magnetic field residual at the target point is found as $\Delta \mathbf{B} = - (v_y, v_x, v_z)$, and the CHAOS model value at that location ($n \leq 20$ for the static field, and $n \leq 8$ for the first time derivative) is finally added. This approach is repeated for each of the 60 months of the time-interval 2001–2005.

In a previous study, we found a remarkable agreement between the satellite monthly means and the corresponding observatory values [7] and presented comparisons for the three observatories Niemegk (Germany), Hermanus (South Africa), and Kakioka (Japan), as well as correlation statistics for 22 observatories. We concluded that satellite monthly means can be used to monitor the time change of the Earth’s magnetic field, similar to observatory data.

This successful validation of the approach encouraged us to determine satellite monthly means on a regular grid (colatitude $\theta = 0^\circ, 5^\circ \ldots 180^\circ$, longitude $\phi = 0^\circ, 5^\circ \ldots 355^\circ$), for the 60 months of the time-interval 2001–2005 and the three components $X$, $Y$ and $Z$.

As an example, Fig. 2 shows $dZ/dt$ at 400 km altitude. The left end-point of each curve corresponds to epoch 2001.0, whereas the right end-point corresponds to epoch 2006.0. The mean value was subtracted from each time series. Virtual observatory locations are indicated by single dots (although we derive values on a $5^\circ \times 5^\circ$ grid, we here only present result on a coarser grid). Also shown are the internal field predictions of CHAOS and of the model described in Section 3. At first glance a clear agreement between the general time behavior of observations and model predictions exist. However, the observations contain more short-period variations compared to the models, in agreement with the results of Mandra and Olsen [7]. An example is the behavior of $dZ/dt$ in the Eastern Asian region during the first years of the considered period. Note the strong variation at polar latitudes, caused by contributions from electric currents in the polar ionosphere. But also at non-polar latitudes there is considerable scatter of the monthly mean values; the average root-mean-squared difference between observations and the CHAOS internal field model is 5.9 nT/yr. In the following section we perform a separation of the observed signal into internal, respectively external contributions, to investigate whether parts of this short-period variation can be explained by magnetospheric field variations.

### 3. Spherical harmonic analysis

Contrary to the traditional way of deriving field models applying a Least Squares fit to the raw magnetic field observations, the availability of vector data on a regular grid enables application of a spherical harmonic transform, which yields spherical harmonic coefficients that are independent of the model parameterization (for instance the selection of coefficients to be determined), due to the orthogonality of spherical harmonics. We perform such a spherical harmonic transform of the monthly means on the regular grid, separately for the vertical component $Z$ and the horizontal components $X$, $Y$ and estimate internal coefficients $g^m_n$, $h^m_n$, and external coefficients $\hat{q}^m_n$, $s^m_n$ for $n = 1 \ldots 20$ and $m = 0 \ldots n$, for each of the 60 months. In addition, following Backus [10], we also derive toroidal expansion coefficients $t^{m,c}_n$, $t^{m,s}_n$, up to $n = 20$. We thus assume that the magnetic field at 400 km altitude,

$$\mathbf{B} = - \nabla V + \nabla \times \hat{r} \Psi,$$

consists of a part that is described by a Laplacian potential,

$$V = a \sum_{n=1}^{N} \sum_{m=0}^{n} \left( g^m_n \cos m\phi + h^m_n \sin m\phi \right) \left( \frac{\mu}{r} \right)^{n+1} P^m_n$$

$$+ a \sum_{n=1}^{N} \sum_{m=0}^{n} \left( q^m_n \cos m\phi + s^m_n \sin m\phi \right) \left( \frac{r}{a} \right)^n P^m_n,$$

(2)
and a part that is described by a toroidal scalar

$$\Psi = a \sum_{n=1}^{N} \sum_{m=0}^{n} (j_n^{m,\phi} \cos m\phi + i_n^{m,\phi} \sin m\phi) P_n^m,$$

where $\theta, \phi$ are geographic co-latitude and longitude, $a=6371.2$ km is a reference radius, $P_n^m (\cos \theta)$ are the associated Schmidt semi-normalized Legendre functions, and $r=a+400$ km is the radius corresponding to the 400 km altitude of the virtual observatories. The maximum spherical harmonic degree is taken as $N=20$.

The time dependence of each Gauss coefficient is finally approximated by cubic $B$-splines with 6 month knot separation. The coefficients for each of the 60 months, as well as their spline representation, are available at www.spacecenter.dk/magnetic-models/.

It turns out that most of the energy of the external field is concentrated in the degree $n=1$ coefficients, and also the toroidal coefficients are only significantly non-zero for $n=1, m=0$. Toroidal coefficients with $m=0$ only affect the $Y$ component, which could be the reason for the poor correlation between satellite and observatory monthly means of $dY/dt$, reported by Mandea and Olsen [7]. Let us note that observatory data are free of any toroidal field contributions since no toroidal field exists in the non-conducting lower atmosphere. A non-zero toroidal field corresponds to electric currents at satellite altitude, and although the monthly means are constructed (cf. Section 2) assuming that $B$ is a potential field (i.e., there are no currents), space–time aliasing may lead to a global non-potential field that is not vanishing.

Figs. 3 and 4 show time series of the first time derivative of the internal Gauss coefficients $d g_n^m/dt$ and $d h_n^m/dt$ for $n=1–6$. 12-month running means of the first differences of a given coefficient (symbols) and the corresponding model values (curves) are presented.

How accurate are the obtained Gauss coefficients $g_n^m$ and $h_n^m$? Visual examination suggests a somehow larger scatter of the low-order coefficients. The scatter can be used as an indication of the coefficient accuracy. Lowes and Olsen [11] investigated the error of spherical harmonic geomagnetic models derived from satellite data in the classical way (least squares fit to individual

![Fig. 2. Time series of $dZ/dt$ (12-month running mean of first differences) at 400 km altitude, for the time-interval 2001–2005. Satellite data are shown in blue, predicted values of the CHAOS model (internal only) in red, predicted values of the new model (internal only) in green. Locations of the "virtual observatories" are shown by black dots.](image-url)
satellite measurements) and found larger errors (standard deviations) for near-zonal \((m \text{ close to zero})\) and near-sectorial \((m \text{ close to } n)\) coefficients. Our error estimates, based on the scatter of the 60 monthly values around the spline-fitted curve, are shown in the left part of Fig. 5. We also find much enhanced error of the zonal coefficients. It is likely that this enhancement is due to variations of the magnetospheric ring-current (which is dominated by expansion coefficients with \(m=0\)) on time-scales shorter than the monthly intervals considered here. The empirical expression

\[
s = 1.83e^{-0.15n-0.95m+0.10m^2} \text{nT/yr},
\]

shown in the right panel of the figure, is found to be a good approximation for the dependence of the observed

Fig. 3. First time derivatives, \(dg^0/dt, dh^0/dt\), of internal Gauss coefficients, in nT/yr. Symbols represent 12-month running mean of first differences and curves the spline fits to the monthly values (green) and predictions of the CHAOS model (red).
Fig. 4. Continuation of Fig. 3.

Fig. 5. Left: standard deviation (in nT/yr) of difference between the first time derivative of observed and fitted internal Gauss coefficients (i.e. the symbols and the green curve of Figs. 3 and 4), in dependence on degree \( n \) and order \( m \). Positive orders \( m \) refer to the coefficients \( g_{n}^{m} \), while negative orders refer to the coefficients \( h_{n}^{m} \). Right: empirical expression \( \sigma = 1.83e^{-0.15n - 0.95m + 0.10m^2} \) nT/yr describing the dependence of the observed standard deviations on \( n \) and \( m \).
standard deviations on \(n\) and \(m\). Typical values are about 1 nT/yr for the zonal coefficients, and less than 0.3 nT/yr for coefficients with \(m\geq1\). Note that these standard deviations refer to the individual monthly values. The error of the spline-smoothed model values is smaller, though difficult to quantify: from the number of degrees of freedom one would expect their standard deviation to be about \(\sqrt{60-10} \approx 7\) times smaller than that of the monthly values, since the curve is parameterized by 10 spline-coefficients, fitted to 60 data points. From this error analysis we conclude that the variation around year 2003 seen in some of the coefficients of Figs. 3 and 4 is significant. Most prominent is the variation in \(h_5^2\), but also \(g_3^2\), \(g_3^3\), \(g_4^4\) and \(h_5^1\) change around year 2003. Some zonal coefficients also change behavior near that time instant (for instance \(g_2^0\) and \(g_5^0\)), but the scatter of the monthly values is too high to isolate a statistical significant variation around 2003.

Since the satellite observations are taken at about 400 km altitude, ionospheric contributions (which are mainly due to currents in the \(E\)-layer at about 100 km altitude) are of internal origin and cannot be separated by means of a spherical harmonic expansion. The external coefficients \(q_n^m\) and \(s_n^m\) of Eq. (2) represent therefore only magnetospheric, but not ionospheric, contributions. First time derivatives of the external coefficients \(dq_n^m/dt\),

\[\frac{dq_n^m}{dt}, \quad n = 1-3, \quad \text{and of the toroidal coefficient } \frac{d\hat{t}_t^1}{dt}, \quad \text{in nT/yr. Note the different scale compared to Figs. 3 and 4.}\]

\[\text{Fig. 6. First differences of external coefficients } \frac{dq_n^m}{dt}, \quad n = 1-3, \quad \text{and of the toroidal coefficient } \frac{d\hat{t}_t^1}{dt}, \quad \text{in nT/yr. Note the different scale compared to Figs. 3 and 4.}\]

\[\text{Fig. 7. As Fig. 2, but after removing monthly estimates of the external field from the observations. Satellite data are shown in blue, predicted values of the CHAOS model (internal only) in red, predicted values of the new model (internal only) in green. Polar regions have been excluded due to their strong contamination by ionospheric current systems.}\]

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of the toroidal coefficient \( d_{t10} \) are displayed in Fig. 6. Note-worthy is the strong variation in \( q_{10} \) and \( t_{10} \) (of up to 20 nT peak-to-peak), which exceeds by far the variation of the internal coefficients. In particular, there is an increase of \( q_{10} \) after 2002, followed by a reduction in 2004. A similar pattern might be present in the internal coefficient \( g_{10} \), though of much reduced amplitude and partly masked by the scatter of the monthly values. Induction in the electrical conducting mantle by an external variation in \( q_{10} \) of 10 nT/yr amplitude and one year period would produce an internal, induced, signal in \( g_{10} \) of about 1.5 to 2 nT/yr, if a realistic model of mantle conductivity is considered (e.g. [12]). This demonstrates the difficulty of extracting the core field variation of \( g_{10} \), since it is easily masked by induced contributions.

Fig. 8. First time derivatives, \( \frac{dX}{dt} \), \( \frac{dY}{dt} \), and \( \frac{dZ}{dt} \), for the Niemegk (NGK), Hermanus (HER) and Kakioka (KAK) observatories. Symbols refer to observations (12-month running mean of first differences), whereas the solid curves indicate predicted values of the \textit{CHAOS} model (internal only) in red, predicted values of the new model (internal only) in green, and internal plus external part of the new model in blue.

Is the well-correlated short-period signal detected in ground and satellite monthly means caused by internal or external sources? Similar to Fig. 2, a map of \( \frac{dZ}{dt} \) at 400 km altitude, but after removal of external (magneto-spheric) field contribution estimated separately for each month, is shown in Fig. 7 (note that a toroidal field does not contribute to \( Z \)). Since only the magneto-spheric field is removed, iono-spheric contributions are still present, especially at polar latitudes. Polar regions have therefore been excluded from Fig. 7. At non-polar latitudes, however, the correction reduces the average root-mean-squared difference between observations and the \textit{CHAOS} internal field model almost by a factor of 2: from 5.9 nT/yr (which corresponds to the uncorrected values shown in Fig. 2) to 3.0 nT/yr. The jerk around 2003 is now more clearly visible, for instance when comparing the field changes in Central Asia.

Let us return to the observatory data analyzed and shown in Mandea and Olsen [7]. An interesting test is to compare the previous results with the new ones, obtained when external contributions are accounted for. In Fig. 8 we present observatory data, i.e. the 12-month running mean of first differences, as well as model predictions, for the same three observatories as analyzed by Mandea and Olsen [7] (cf. their Fig. 3). The internal field predictions of the \textit{CHAOS} model and of the new model do not follow the short-period variations of the observatory data (symbols). However, adding the external field yields model predictions that are in slightly better agreement with the observatory data. It should be noted that all models are entirely based on satellite data; no observatory data were used to obtain these models. However, although adding the external field brings the model values closer to the observations (see for instance the reduction of \( \frac{dZ}{dt} \) at Hermanus near 2003, or the corresponding enhancement at Niemegk), there are still short period variations in the data that are not described by the model. The reason for this is unknown.

4. Discussion and conclusions

Taking advantage of more than five years of CHAMP data we investigated the global characteristics of the
2003 geomagnetic jerk. Fig. 7 clearly shows a complete different pattern of the secular variation in different regions. This is confirmed by the upper left part of Fig. 9, which shows a map of the second time derivative, \( d^2 Z/dt^2 \), for epoch 2003 at the Earth’s surface, as given by the CHAOS model. A region of strong increasing secular variation (\( d^2 Z/dt^2 > 0 \)) is seen in the eastern Indian ocean; secular variation also increases in the central Pacific ocean. Decreasing secular variation (\( d^2 Z/dt^2 < 0 \)) is to be remarked in the southern African region (continental and surrounding oceanic area).

In addition to these regional different trends of secular variation (i.e. differences of \( d^2 Z/dt^2 \)), there is a change of slope of \( dZ/dt \) (i.e. a jump of \( d^2 Z/dt^2 \)) around 2003 in some areas, which indicates the jerk of 2003. Since a jerk is manifested as an abrupt change in the second time derivative, non-zero values of

\[
\Delta \ddot{Z} = \left. \ddot{Z} \right|_{2004.5} - \left. \ddot{Z} \right|_{2001.5}
\]

indicate the presence of a jerk around 2003. A map of \( \Delta \ddot{Z} \) is shown in the upper right part of Fig. 9. It is very clearly seen that the jerk of 2003 mainly happens in a rather limited region around the 90° E meridian, although weak effects are also visible outside this region. Although there is a strong jerk signal in the coefficient \( h_2^2 \), this coefficient alone cannot explain the pattern shown in the figure. A few other spherical harmonic coefficients contribute, too; the most significant are \( \Delta g_1^2 = 2.7 \text{ nT/yr}^2 \), \( \Delta g_2^2 = 2.2 \text{ nT/yr}^2 \), \( \Delta g_3^2 = 1.2 \text{ nT/yr}^2 \), \( \Delta h_2^1 = 1.5 \text{ nT/yr}^2 \), \( \Delta g_3^1 = -0.18 \text{ nT/yr}^2 \), \( \Delta g_3^3 = -0.88 \text{ nT/yr}^2 \), \( \Delta g_4^2 = -0.63 \text{ nT/yr}^2 \) and \( \Delta h_4^3 = -0.60 \text{ nT/yr}^2 \). The jerk signal maximum is near 17° S, 107° E (\( \Delta \ddot{Z} = +20 \text{ nT/yr}^2 \)), while its minimum is near 34° N, 77° E (\( \Delta \ddot{Z} = -26 \text{ nT/yr}^2 \)). Interestingly this region of maximum jerk strength, \( \Delta \ddot{Z} \), (to the north and south of the equator near the 90° E meridian, cf. upper right panel of Fig. 9) roughly coincides with the region of maximum secular acceleration (shown in the upper left part of this figure).

For completeness, the lower panel of the figure shows the jerk strengths, \( \Delta \ddot{X} \) and \( \Delta \ddot{Y} \), in the horizontal components. They are considerable smaller compared to the signature in the vertical component, in agreement with the finding by Sabaka et al. [5] for previous jerks. It is interesting to note that jerk studies have been mainly done using observations of the \( Y \)-component (since this is the component that is least contaminated by external fields), although the jerk strength is strongest in the \( Z \)-component. For the Niemegk observatory in central Europe the jerk strength in the East–West component is slightly negative (\( \Delta \ddot{Y} = -3.4 \text{ nT/yr}^2 \)), in agreement with

![Fig. 9. Top: Maps of \( \ddot{Z} \) for epoch 2003 (left) and of \( \Delta \ddot{Z} \) (right) at the Earth’s surface, as given by the CHAOS model. Units are nT/yr². Bottom: Maps of \( \Delta \ddot{X} \) and \( \Delta \ddot{Y} \) at the Earth’s surface. Contourline interval is 4 nT/yr².](image-url)
obtained independently for the southern hemisphere location. The intersection time of 2003.3 obtained for the northern hemisphere location is very close to the value of 2003.4. The piecewise trends. The intersection time of 2003.3 obtained for the negative, jerk signature. The straight lines represent best-fitted linear trends. The locations of maximum jerk strength in the vertical component and fitted piecewise linear trends, 

$$\hat{Z} = \begin{cases} \dot{z}_1 + \ddot{z}_1 (t-t_{\text{jerk}}), & t < t_{\text{jerk}} \\ \dot{z}_2 + \ddot{z}_2 (t-t_{\text{jerk}}), & t > t_{\text{jerk}}. \end{cases}$$

We solved for $z_1$, $\ddot{z}_1$, $z_2$, $\ddot{z}_2$ and the intersection time $t_{\text{jerk}}$ using robust Least Squares, requiring continuity of $\hat{Z}$ at $t = t_{\text{jerk}}$ (i.e., $\dot{z}_1 = \dot{z}_2$). Time series of $dZ/dt$ at the two locations are shown in Fig. 10, together with the fitted piecewise linear functions. The best-fitting intersection time for the location of the jerks signal maximum in the southern hemisphere ($17^\circ$ S, $107^\circ$ E) is $t_{\text{jerk}} = 2003.4$, while that for the location of the signal minimum in the northern hemisphere ($34^\circ$ N, $77^\circ$ E) is $t_{\text{jerk}} = 2003.3$. Thus the two times are very similar. From this result we conclude that the jerk occurred simultaneously in the northern and southern hemispheres during the first months of the year 2003. Note, however, that these numbers refer to the time when the jerk reaches the Earth’s surface after traveling from the core through the mantle, which acts as a filter: Due to the electrical conductivity of the mantle the phenomena occurred some time (probably some months) earlier in the core [13].

The jerk strength (i.e. the difference in slope of $dZ/dt$ before and after the jerk) is $\Delta \dot{Z} = \ddot{z}_2 - \ddot{z}_1 = 13.4$ nT/yr$^2$ for the southern hemisphere maximum; that of the northern hemisphere minimum is $\Delta \dot{Z} = \ddot{z}_2 - \ddot{z}_1 = -3.9 - 9.3 = -13.2$ nT/yr$^2$, in reasonable agreement with the values derived from the CHAOS model.

A piecewise linear fit to time series of the expansion coefficient $h_2^2$ shown in Fig. 3 yields an intersection time $t_{\text{jerk}} = 2003.5$ and a jerk strength of $\Delta h_2^2 = \ddot{z}_2 - \ddot{z}_1 = 0.98 + 0.78 = 1.76$ nT/yr$^2$.

These results give valuable hints for understanding geomagnetic jerks. Various explanations on the origin of jerks have recently been suggested. They have been thought either as produced by a jump in acceleration of the fluid motion at the core–mantle boundary [14], as an instability starting at the core–mantle boundary in the form of a density heterogeneity in the very top layer of the core [15], or considered to be created by torsional oscillations of the core [16]. If the latter hypothesis is assessed, one may conclude that the 2003 geomagnetic jerk, with its spatial distribution well constrained by globally distributed satellite data, occurs only in a rather restricted region, due to the morphology of the main magnetic field. This implies that it might be possible to explain why some jerks are very well defined and dominate the secular variation trend over several years (see, for example, the jerks of 1925, 1969, and 1979 in Fig. 1), while others occur over short-term periods (as secular variation changes around 1913, 1918, 1948, 1956, 1996, 1999, 2003).

Is there other evidence for a jerk around 2003? Holme and de Viron [8] found a clear correlation between the time of geomagnetic jerks and features in length-of-day (LOD) variations. After removal of the effect of atmospheric angular momentum from the

![Fig. 10. Time series of $dZ/dt$ at 400 km altitude at the two locations ($17^\circ$ S, $107^\circ$ E) and ($34^\circ$ N, $77^\circ$ E) of maximum positive, resp. negative, jerk signature. The straight lines represent best-fitted linear piecewise trends. The intersection time of 2003.3 obtained for the northern hemisphere location is very close to the value of 2003.4 obtained independently for the southern hemisphere location.](image)

![Fig. 11. Smoothed changes in length-of-day (LOD) data for two levels of smoothing. The solid curve is more heavily smoothed compared with the dashed one. The gray regions indicate times of short-period “wiggles” in d(LOD)/dt, which may be related to geomagnetic jerks. There is noticeable evidence for a geomagnetic jerk around 2003 in the length-of-day variation. (By courtesy of Dr. R. Holme).](image)
observed LOD, they derived smooth high-resolution time series of LOD and d(LOD)/d$t$. Fig. 3 of their paper shows a convincing agreement between the occurrence of short-period “wiggles” in d(LOD)/d$t$ and geomagnetic jerks. An updated version of that figure, over the time-span 1996–2006, is presented in Holme and de Viron [17]. Fig. 11 (Holme, private communication, 2006) is based on that work. In addition to showing enhanced extrema, the less smoothed curve contains additional “wiggles” around 1999 (for which a jerk has been reported by Manda et al. [3]) and 2003, indicated by the gray areas. There is therefore also evidence for a geomagnetic jerk around 2003 in the length-of-day variation.

In the present paper we demonstrated that magnetic satellites represent a good platform from which data containing jerk signatures can be extracted. The outstanding advantage is that, for the first time, an impulse in the secular variation could be studied directly and globally from magnetic data. From our analysis we conclude that geomagnetic jerks are not worldwide in occurrence — at least not the jerk of 2003.

The present work suggests that studies of secular variation on very short periods of 2 to 3 yr can be developed, with important consequences in inferring an upper limit for the mantle electrical conductivity. Moreover, the present study confirms a link between geomagnetic jerks and LOD variation.

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