CHAOS-2 – A Geomagnetic Field Model Derived from One Decade of Continuous Satellite Data

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SUMMARY
We have derived a model of the near-Earth’s magnetic field using more than 10 years of high-precision geomagnetic measurements from the three satellites Ørsted, CHAMP and SAC-C. This model is an update of the two previous models, CHAOS (Olsen et al. 2006) and xCHAOS (Olsen and Mandea 2008). Data selection and model parameterization follow closely those chosen for deriving these models. The main difference concerns the maximum spherical harmonic degree of the static field ($n = 60$ compared to $n = 50$ for CHAOS and xCHAOS), and of the core field time changes, for which spherical harmonic expansion coefficients up to $n = 20$ are described by order 5 splines (with 6-month knot spacing) spanning the years 1997.0 to 2009.5. Compared to its predecessors, the temporal regularization of the CHAOS-2 model is also modified. Indeed, second and higher order time derivatives of the core field are damped by minimizing the second time derivative of the squared magnetic field intensity at the core mantle boundary. The CHAOS-2 model describes rapid time changes, as monitored by the ground magnetic observatories, much better than its predecessors.

Key words: Geomagnetism, Earth’s magnetic field, Geomagnetic secular variation, Satellite, Spherical harmonics, Lithosphere

1 INTRODUCTION
The launch of the Ørsted satellite in February 1999 marked the beginning of the International Decade of Geopotential Research. Ørsted was followed by the CHAMP satellite and the SAC-C satellite, launched in July and November 2000, respectively. All three missions carry essentially the same instrumentation and provide high-quality and high-resolution magnetic field observations from space. The three satellites sense the various internal and external field contributions differently, due to their different altitudes (Ørsted: 630 – 860 km, CHAMP: 310 – 450 km; SAC-C: 700 km) and drift rates through local time.

Various magnetic field models of increasing complexity have been derived using data from these satellites, from “snapshot models” that describe the field at a specific epoch (Olsen et al. 2000a,b) over models for which the time dependence of the core field is parameterized by a Taylor expansion in time (Olsen 2002; Langlais et al. 2003; Maus et al. 2005, 2006; Thomson and Lesur 2007) to models with spline-representation of the time dependence (Olsen et al. 2006; Lesur et al. 2008; Olsen and Mandea 2008). The present paper describes an updated version of the CHAOS geomagnetic field model of Olsen et al. (2006), denoted as CHAOS-2 (see Olsen and Mandea (2008) for a description of xCHAOS, a predecessor of CHAOS-2).

The goal of CHAOS-2 is to provide a good representation of the core field changes by making use of 10 years of continuous high-precision satellite magnetic observations. In particular, the model aims at describing core field changes with high spatial resolution of the first time derivative (linear secular variation), and high temporal resolution (rapid field changes).

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2 DATA SELECTION AND MODEL PARAMETERIZATION

We use Ørsted scalar and vector data between March 1999 and March 2009 (vector data only until December 2005), CHAMP vector and scalar data between August 2000 and March 2009 (vector data only after January 2001), and SAC-C scalar data between January 2001 and December 2004. These satellite data are selected using the same criteria as for the CHAOS model (Olsen et al. 2006): 1) at all latitudes we require that the $D_{st}$-index measuring the strength of the magnetospheric ring-current does not change by more than 2 nT/hr; 2) at non-polar latitudes (equatorward of $\pm 60^\circ$ dipole latitude) we require for the geomagnetic activity index $K_p \leq 2$; 3) for regions poleward of $60^\circ$ dipole latitude the merging electric field at the magnetopause has to be less than $0.8 \text{ mV/m}$; 4) only data from dark regions (sun $10^\circ$ below horizon) are used; 5) vector data are taken for dipole latitudes equatorward of $\pm 60^\circ$; 6) scalar data are used for regions poleward of $\pm 60^\circ$ or if attitude data were not available; 7) non-polar CHAMP data are only used from local time past midnight. Data sampling interval is 60 seconds; weights proportional to $\sin \theta$ (where $\theta$ is the geographic co-latitude) are applied to simulate an equal-area distribution. Anisotropic errors due to attitude uncertainty (Holme and Bloxham 1996; Holme 2000) are considered for all Ørsted vector data and for CHAMP vector data when attitude data from only one star imager are available.

As an example of the data distribution in time, Figure 1 shows the total number of non-polar magnetic observations for each month. The gaps in the selected CHAMP data about every 130 days is due to the local drift rate of the CHAMP orbit plane and the fact that only CHAMP data past midnight are used. Data from the two other satellites, with their different orbital drift rate, are very useful in filling these gaps. Periods for which less data are available (for instance around 2003) are due to increased geomagnetic activity. Problems with the attitude stability are the reason for the Ørsted data gap around 2007.

To extend the model back in time beyond February 1999 (the launch of the Ørsted satellite), we also use annual differences of observatory monthly means of the North, East and downward components $(X,Y,Z)$ for the years 1997 to 2006 (annual difference means that the value at time $t$ is obtained by taking the difference between those at $t+6$ months and $t-6$ months, thereby eliminating an annual variation in the data). This yields 9,860 values of the first time derivative of the vector components, $(dX/dt, dY/dt, dZ/dt)$ for 105 observatories. These data only contribute to the part of the model that describes the time-changes in the core field. To account for correlated errors due to magnetospheric contributions, we applied the approach of Wardinski and Holme (2006) and weighted the vector components of each observatory according to its 3 x 3 data covariance matrix (including non-diagonal elements, i.e. correlation between the different components). As will be demonstrated later, adding the observatory data yields a reliable description of the core field changes prior to 1999 (i.e. before satellite data are available) but hardly change the model for the other years, for which the time changes are well resolved by the satellite data.

Parameterization of the CHAOS-2 model follows closely those of CHAOS and xCHAOS (see Olsen et al. (2006) for further details). The model consists of two parts: spherical harmonic expansion coefficients describing the magnetic field vector in an Earth-Centered Earth-Fixed (ECEF) coordinate system, and sets of Euler angles needed to rotate the vector readings from the magnetometer frame to the star imager frame. The magnetic field vector in the ECEF frame, $\mathbf{B} = -\nabla V$, is derived from a magnetic scalar potential $V = V^{\text{int}} + V^{\text{ext}}$ consisting of
Figure 2. Schematic of the first six years of the 12.5 years time span covered by the model, showing the first 16 (out of 29 in total) B-spline basic functions, $M_i(t), i = 1 - 29$, used to represent the time change of each internal Gauss coefficient of degree $n \leq 20$. There are 24 interior knots and 5 exterior knots at each endpoint 1997.0 and 2009.5.

A part, $V^{\text{int}}$, describing internal (core and crustal) sources, and a part, $V^{\text{ext}}$, describing external (mainly magnetospheric) sources (including their Earth-induced counterparts). Both are expanded in terms of spherical harmonics.

For the internal part this yields

$$V^{\text{int}} = a \sum_{n=1}^{N_{\text{int}}} \sum_{m=0}^{n} (g_n^m \cos m\phi + h_n^m \sin m\phi) \left(\frac{a}{r}\right)^{n+1} P_n^m (\cos \theta)$$

(1)

where $a = 6371.2$ km is a reference radius, $(r, \theta, \phi)$ are geographic coordinates, $P_n^m$ are the associated Schmidt semi-normalized Legendre functions, $\{g_n^m, h_n^m\}$ are the Gauss coefficients describing internal sources, and $N_{\text{int}}$ is the maximum degree and order of the internal expansion, which is taken here to $N_{\text{int}} = 60$ (for CHAOS and xCHAOS the maximum degree was $N_{\text{int}} = 50$).

The time dependence of the internal Gauss coefficients $\{g_n^m(t), h_n^m(t)\}$ up to $n = 20$ is described by B-splines (Schumaker 1981; De Boor 2001) in the time interval 1997.0 to 2009.5. However, contrary to the CHAOS model and many other geomagnetic field models which use cubic (i.e. order 4) B-splines (Bloxham 1985; Jackson et al. 2000; Wardinski and Holme 2006; Olsen et al. 2006), we prefer to use order 5 B-splines, similar to the models CM4 (Sabaka et al. 2004) and GRIMM (Lesur et al. 2008). Splines of order 4 result in a piecewise linear representation of $\mathbf{B}$, which is not favorable for studying rapid core field changes and geomagnetic jerks. Order 5 splines result in a more smooth representation of $\mathbf{B}$ and are therefore preferable. In order to be able to describe rapid field temporal variations of the core field, we use a 6-month knot separation and four-fold knots at the endpoints, $t = 1997.0$ and $t = 2009.5$. This yields 24 interior knots (at 1997.5, 1998.0, 2000.0 and 2002.0) and 5 exterior knots at each endpoint, 1997.0 and 2009.5, resulting in 29 basic B-spline functions, $M_i(t)$. The first 6 years of the total 12.5 year time span covered by the model contain 16 of these basis functions and are shown in Figure 2; the second half (2003.0 to 2009.5) is symmetric with respect to $t = 2003.25$. We define as a typical resolution or smoothing time $\tau$ the “width” where the spline function drops to half of its maximum value. For the given parameterization (order 5 splines with 6-month knot separation) this results in $\tau = 6.9$ months for $l = 5$ to 25 as shown in Figure 2 for the spline function $M_{12}(t)$ (spline functions for $l = 1 - 4$ and $l = 26 - 29$ are influenced by edge effects and have different values of $\tau$). In section 3 we use this definition of smoothing time $\tau$ to investigate the effect of model regularization on the temporal resolution of each Gauss coefficient. Time-dependent terms (for degrees $n = 1 - 20$) and static terms (for $n = 21 - 60$) together results in a total of 16,040 internal Gauss coefficients.

The external part of the potential, $V^{\text{ext}}$, describes large-scale magnetospheric sources and is parameterized similar as for the CHAOS model: contributions from far magnetospheric current systems (e.g., tail currents) are expanded in Geocentric Solar Magnetospheric (GSM) coordinates (up to $n = 2$), while contributions from the near magnetosphere (e.g., the magnetospheric ring current) are expanded in the Solar Magnetic (SM) coordinate system (also up to $n = 2$). The time dependence of degree-1 magnetospheric terms in SM coordinates is param-
To assess the quality of the spatial description it is helpful to look at the Mauersberger-Lowes spectra at a given epoch. The static field and temporal structure of the secular variation are characterized by the $E_{st}$ and $I_{st}$ indices, which correspond to the external, respectively induced, part of the $D_{st}$ index of global magnetospheric activity (see Maus and Weidelt (2004) and Olsen et al. (2005) for a description of the decomposition of $D_{st} = E_{st} + I_{st}$). In addition, we solve for large-scale time-varying degree-1 coefficients in bins of 12 hours length (for $n = 1$, $m = 0$), resp. 5 days length (for $n = m = 1$), similar as for the CHAOS model (see Olsen et al. (2006) for details). This gives a total of 5,825 external coefficients.

Finally, and again following the CHAOS model parameterization, we perform an in-flight instrument calibration and solve for the Euler angles of the rotation between the coordinate systems of the vector magnetometer and of the star sensor that provide attitude information. For the Ørsted data, this yields two sets of Euler angles, while for CHAMP we solve for Euler angles in bins of 10 days (resulting in 195 sets of angles), to account for the thermo-mechanical instabilities of the magnetometer/star-sensor system. This yields additional $3 \times (2 + 195) = 591$ model parameters. The total number of model parameters is $16,040 + 5,825 + 591 = 22,456$.

These model parameters are estimated by means of a regularized Iteratively Reweighted Least-Squares approach using Huber weights, minimizing the chi-squared misfit

$$\chi^2 = e^T C^{-1} e + \lambda m^T \Lambda m$$

where $m$ is the model vector and the residuals vector $e = d_{obs} - d_{mod}$ is the difference between observation $d_{obs}$ and model prediction $d_{mod}$. The data covariance matrix $C$ contains the data errors multiplied by Huber weights (to account for the non-Gaussian distribution of the data residuals); its non-diagonal elements accounts for the anisotropic errors due to attitude noise (see Olsen (2002) for details). $\Lambda$ is a block diagonal regularization matrix which constrains the second and higher order time derivatives of the core field. Only elements corresponding to the spline coefficients are non-zero and chosen such that they minimize the mean squared magnitude of $\dot{\mathbf{B}}$, integrated over the core surface (radius $c = 3485$ km) and averaged over time. This damping is different from that used for CHAOS (for which $|\mathbf{B}|^2$ is minimized at Earth’s surface) and xCHAOS (for which the squared second time derivative of the scalar potential $V$ is minimized at the core surface). The parameter $\lambda$ controls the strength of this regularization, with $\lambda = 0$ corresponding to an undamped model. We derived two models: a smoother (more damped) model, called CHAOS-2s ($\lambda = 3 \times (\text{nT/yr}^2)^{-2}$), and a rougher (less damped) one, called CHAOS-2r ($\lambda = 3 \times 10^{-2}$ (nT/yr$^2$)$^{-2}$). Note that this regularization directly neither affects the static field nor the first time derivative, which are left undamped.

### 3 RESULTS AND DISCUSSION

Number of data points, residual means and root mean squared (rms) values of the two model versions are listed in Table 1. Statistics for the satellite vector data is given in a coordinate system that is defined by the bore-sight of the star imager and the ambient field direction (cf. Olsen et al. (2000b) for details). Both components $B_\perp$ and $B_3$ are perpendicular to the main field, while $B_B$ is in its direction. The CHAOS-2 statistics are similar to those of the CHAOS model (cf. Table 1 of Olsen et al. (2006)) with an overall scalar misfit at non-polar latitudes of less than 3 nT rms.

### Spatial Spectra

As mentioned before, one goal of CHAOS-2 is to provide a good description of the spatial and temporal structure of the secular variation. To assess the quality of the spatial description it is helpful to look at the Mauersberger-Lowes spectra at a given epoch. The static field and

<table>
<thead>
<tr>
<th>component</th>
<th>CHAOS-2s</th>
<th>CHAOS-2r</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$N$</td>
<td>mean</td>
</tr>
<tr>
<td>satellite</td>
<td></td>
<td></td>
</tr>
<tr>
<td>all</td>
<td>274,564</td>
<td>-0.04</td>
</tr>
<tr>
<td>$F_{\text{polar}}$</td>
<td>794,522</td>
<td>0.04</td>
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<tr>
<td>$F_{\text{nonpolar}} + B_B$</td>
<td>107,891</td>
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</tr>
<tr>
<td>Ørsted</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$F_{\text{polar}}$</td>
<td>399,936</td>
<td>0.34</td>
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<tr>
<td>$B_\perp$</td>
<td>144,592</td>
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</tr>
<tr>
<td>$B_3$</td>
<td>144,592</td>
<td>-0.01</td>
</tr>
<tr>
<td>CHAMP</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$F_{\text{polar}}$</td>
<td>131,344</td>
<td>-0.91</td>
</tr>
<tr>
<td>$F_{\text{nonpolar}} + B_B$</td>
<td>251,046</td>
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</tr>
<tr>
<td>$B_\perp$</td>
<td>236,848</td>
<td>0.06</td>
</tr>
<tr>
<td>$B_3$</td>
<td>218,860</td>
<td>-0.01</td>
</tr>
<tr>
<td>SAC-C</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$F_{\text{polar}}$</td>
<td>35,329</td>
<td>-0.02</td>
</tr>
<tr>
<td>$F_{\text{nonpolar}}$</td>
<td>143,540</td>
<td>0.16</td>
</tr>
<tr>
<td>observatory</td>
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</tr>
<tr>
<td>$dX/dt$</td>
<td>9,860</td>
<td>2.74</td>
</tr>
<tr>
<td>$dY/dt$</td>
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<td>1.77</td>
</tr>
<tr>
<td>$dZ/dt$</td>
<td>9,860</td>
<td>0.92</td>
</tr>
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</table>
first time derivative coefficients of the two model versions CHAOS-2s and CHAOS-2r are very similar (although of course not identical), especially for degrees \( n > 10 \). Let us in following concentrate on the smoother model CHAOS-2s. Figure 3 shows spectra of the first and second time derivatives of various models and is an update of Fig. 2 of Olsen et al. (2006). It demonstrates the improvement in determining secular variation over the last decades, from models derived using Magsat satellite data (Langel and Estes 1985; Langel et al., 1988), to models derived from data taken during the first years of the International Decade (Olsen et al., 2002; Maus et al. 2005) and to the very recent models CHAOS (Olsen et al., 2006), GRIMM (Lesur et al., 2008), and CHAOS-2 (this paper). The spectrum of the xCHAOS model (Olsen and Mandea 2008) is not shown as it is almost identical to that of CHAOS-2. The spectrum of the first time derivative of the latter decreases down to a level of less than \( 10^{-2} \) (nT/yr\(^2\)) for spherical harmonic degrees above \( n = 16 \). This suggests that core field time changes down to spatial scales corresponding to spherical harmonic degree \( n = 15 \) or 16 are robustly described by CHAOS-2.

When looking at the secular variation spectrum in more detail, the increased power at the even spherical harmonic degrees \( n = 14 \) and 14, and to some extend also 12, is striking. Most of the power at degree \( n = 14 \) is in the tesseral coefficients (\( h_{14} = -0.043 \) nT/yr\(^2\)) is by far the largest coefficient of degree \( n = 14 \), followed by \( h_{14} = -0.022 \) nT/yr\(^2\)), and setting the tesseral coefficients for \( n > 10 \) to zero results in a spectrum shown by the dashed curve. It is still unclear whether the increased power of the tesseral coefficients for \( n = 14 \) and 16 is only by chance, or whether it reflects a small-scale low-latitude feature in the secular variation. Finlay and Jackson (2003) found evidence for equatorially dominated magnetic field changes in historic magnetic field data described by the gufm1 model of Jackson et al. (2000); however, this model is spatially regularized and describes only structures corresponding to spherical harmonic degrees \( n \leq 10 \) or so.

Also shown in Figure 3 are spectra of the second time derivative (secular acceleration) for some models. Note that this part of the CHAOS, GRIMM and CHAOS-2 models is damped. Compared to GRIMM, the secular acceleration spectrum of CHAOS-2s has more power at spherical harmonic degrees \( n \leq 3 \), while that of GRIMM is stronger for \( n > 4 \). Note, however, that the secular acceleration power heavily depends on the chosen damping parameter \( \lambda \).

In addition to model version CHAOS-2s we also determined a rougher model version, denoted as CHAOS-2r by reducing the damping parameter \( \lambda \). The spectra shown in Figure 3 are for a certain epoch \( t_0 \). A non-zero secular acceleration (second time derivative) results in time changes of the secular variation (first time derivative). Figure 4 shows these spectra for CHAOS-2s (left, \( \lambda = 3 \cdot 10^{-2} \) nT/yr\(^2\)) and CHAOS-2r (right, \( \lambda = 3 \cdot 10^{-2} \) nT/yr\(^2\)) and various epochs. The color of the spectrum indicates the model epoch, varying from blue (for \( t_0 = 2000.0 \)) to red (for \( t_0 = 2007.0 \)). The secular variation spectra of the two model versions are very similar despite of the different secular acceleration spectra (which is due to the different regularization parameter \( \lambda \) chosen for the two model versions).
Temporal resolution

As shown in Figure 2, the smoothing time of each spline function (except those near the end points) is $\tau = 6.9$ months. In case of a non-regularized model ($\lambda = 0$), this directly maps into the smoothing time of each Gauss coefficient $g_{nm}(t)$, $n = 1 - 20$. However, model regularization results in smoothing times $\tau$ that are different for each Gauss coefficient and time dependent (because of the uneven data distribution in time). Let $A$ be the data kernel matrix that connects the model vector $\mathbf{m}$ with the data vector $\mathbf{d} = A\mathbf{m}$ (for simplicity we here only consider the case of a linear model). The model resolution matrix is defined as (Menke 1984) $R = (A^T A + \lambda \Lambda)^{-1} (A^T A)$. For the case of no regularization ($\lambda = 0$) $R = 1$ is a unit matrix.

Let us assume that the time dependence of each Gauss coefficient is given by one single spline function, for instance $M_{13}(t)$. The left part of Figure 5 shows how this input signal $M_{13}(t)$ is modified due to model regularization, i.e. $M_{13}(t) \rightarrow G_{nm}(t)$, for some Gauss coefficients $g_{nm}^0$ and for the regularization parameters that we have chosen for CHAOS-2s (red) and CHAOS-2r (green), respectively. Similar to our definition of smoothing time $\tau$ for the spline basis function (cf. section 2) we define $\tau_{nm}^m$ for the filtered spline functions $G_{nm}(t)$ for each Gauss coefficient, as illustrated in Figure 5 for $g_{13}^0$ of model CHAOS-2s. The regularization parameter chosen for CHAOS-2r has almost no influence on the temporal resolution of $g_{13}^0$ of that model, which is the reason why $\tau_{13}^1 \approx \tau_{13}^0 = 6.9$ months. However, regularization has stronger influence on higher degree terms (as expected), and results in $\tau_{3}^3 = 7.4$ months and $\tau_{5}^5 = 9.9$ months. For model CHAOS-2s the smoothing times are considerable larger: $\tau_{1}^1 = 8.1$ months, $\tau_{3}^3 = 14.5$ months, and $\tau_{5}^5 = 25.6$ months. Terms of even higher degree are so heavily smoothed that it is difficult to determine a meaningful smoothing time (since the filtered spline function does not drop below half of its maximum value in the considered time span); we find that for degrees $n > 7$ the coefficients of model CHAOS-2s are essentially an average over the whole data period of 12 years. Our analysis confirms that the smoothing time mainly depends on spherical harmonic degree $n$ but is almost independent on the order $m$, as expected for a regularization that depends only on $n$ but not on $m$.

Figure 4. Maurerberger-Lowes spectra of first and second time derivatives at Earth’s surface for CHAOS-2s (left) and CHAOS-2r (right). The different curves correspond to different epochs $t_0$ indicated by the color, from $t_0 = 2000.0$ (blue) in steps of 6 months until $t_0 = 2007.0$ (red).

Figure 5. Filtered spline function output $G_{nm}(t)$ for 2003 (left) and time dependence of smoothing time $\tau_{nm}^m$ (right) for selected Gauss coefficients and for CHAOS-2s (red) and CHAOS-2r (green).
While the left part of Figure 5 shows as an example the smoothing time $\tau_0$ around 2003 (i.e. at the maximum of the spline function $M_{13}(t)$), its right part shows the time dependence of $\tau_0$. The regularization has stronger effect at the beginning because of the less amount of data, which is the reason for the increase of $\tau_0$ before 2002.

Fit to observatory monthly means

An assessment of the quality of the temporal description of CHAOS-2 is possible by comparing observed and modeled field variations as monitored by ground observatories. Figure 6 shows the fit to the first time derivative at the four observatories Niemegk (NGK) in Europe, Kakioka (KAK) in Japan, Guam (GUA) in the Pacific, and Hermanus (HER) in South Africa, for some field models. The CHAOS-2s model (red curve) describes rapid time changes much better than the CHAOS model (magenta curve) and about equally well as the $x$CHAOS model (not shown). Model values of a version of CHAOS-2s obtained without observatory data are shown by the dashed red curve; they differ from CHAOS-2s before 1999 but are very similar for years when satellite data are available.

CHAOS-2s yields a superior description of the observed field variation compared to CHAOS and GRIMM over the entire decade, which is not surprising given the more limited data time span used when deriving the two other models (CHAOS: 1999-2005; GRIMM: 2001-2005). However, there are rapid field variations (for instance in the $Z$-component of KAK and GUA between 2002 and 2004) that are neither described by CHAOS-2s. These changes occur so fast that they cannot be described by splines (of order 5 or less) with knot separation of one year or longer, as it is the case for CHAOS and GRIMM. When trying to fit $dZ/dt$ at KAK, resp. GUA, with splines we find that a knot spacing of 8 months or shorter is needed (which is the reason for changing the knot-spacing from 1 year for CHAOS and $x$CHAOS to 6 months for CHAOS-2).

Are these rapid field changes of core origin, or are they due to contamination by external (ionospheric and magnetospheric) sources? Figure 6 shows that CHAOS-2r describes the rapid field changes seen in the vertical component at KAK and GUA much better than the more heavily regularized version CHAOS-2s. Interestingly, a less regularized model determined from satellite data alone (without observatory data, green dashed curve) fits these rapid field changes, too. Given the different sampling regions (at the ground, resp. above the ionosphere) and data selection criteria of observatory and satellite data (observatory monthly means are determined by averaging all days and all local times, whereas the satellite data used for CHAOS-2 are only taken from geomagnetically quiet times and dark conditions), this agreement indicates that these rapid field changes are of internal (core) origin. To investigate this further we used the CM4 model (Sabaka et al. 2004) and synthesized hourly mean values of the magnetospheric, ionospheric and Earth-induced magnetic field contributions from which we calculated synthetic monthly mean values following usual observatory practice. Comparing the observed monthly means shown in Figure 6 with these synthetic values (not shown) gives further confidence that the rapid field changes are not of external origin.

Let us note that reduction of the damping parameter $\lambda$ results in some field fluctuations that are hardly confirmed by the observatory data (see, for instance, $dY/dt$ at NGK and HER), and it is doubtful whether all small “wiggles” of CHAOS-2r are real. However, the magnitude of these fluctuations is reduced when including observatory data, as expected, which gives us further confidence in the quality of CHAOS-2r, at least at non-polar latitudes.

Are there other independent data (in addition to the ground observations) to assess the temporal resolution of the CHAOS-2 model? Following the approach described in Mandea and Olsen (2006) and Olsen and Mandea (2007), we used CHAMP satellite magnetic vector to determine monthly mean values at a regular grid of “virtual observatories” at 400 km altitude (the mean CHAMP altitude) for the time interval January 2001 to March 2009. Figure 7 is an extension in time of Figure 7 of Olsen and Mandea (2007) by two years and shows the obtained “virtual observatory” time series together with values from CHAOS-2s (red) and CHAOS-2r (green). Also this data set demonstrates that CHAOS-2r describes rapid field changes better than CHAOS-2s, especially at non-polar latitudes. An interesting feature is seen west of Africa, where a jerk-like signature (i.e. a change in slope of the first time derivative, corresponding to a sudden jump in the second time derivative) is seen around 2007. Note that the virtual observatory monthly data means are determined from all CHAMP data (regardless of geomagnetic activity and local time), whereas CHAOS-2 uses less than 20% of all available data. We therefore regard those satellite-based monthly means as an independent data set that allows an assessment of the CHAOS-2 model.

A closer investigation of the curves reveals three areas with interesting secular variation. They can roughly be delimited by the latitudinal bands $-45^\circ$ to $45^\circ$ and, from West to East, by the longitude $-10^\circ$ to $10^\circ$, $30^\circ$ to $50^\circ$, and $70^\circ$ to $90^\circ$. The central region is characterized by a clear V-shape rapid change in the secular variation around 2005, indicating a jerk-like feature. On each side the secular variation is dramatically decreasing (west of $30^\circ$) or increasing (east of $50^\circ$). This is interesting regarding the directional propagation of the jerk-like features.

Finally, we show in Figure 8 a map of $dZ/dt$ at the core mantle boundary. The secular variation spectrum is almost “flat” at that depth, which would result in “ringing” when plotting a truncated spherical harmonic expansion that has not converged. In order to avoid this, we have filtered (damped) the secular variation coefficients according to Wardinski and Holme (2006):

$$g_n^{\text{filtered}} = g_n^{\text{model}} \frac{1}{1 + \mu \left( \frac{n}{2} \right)^{2n+4}}$$

(and similar for $h_n^{\text{model}}$) with $\mu = 3.5 \cdot 10^{-10}$, where $a = 6371.2$ km and $c = 3485$ km are the radii of the Earth’s surface and the outer core, respectively. This filter changes mainly coefficients above $n = 12$ and reduces the amplitude at degree $n = 16$ by a factor of 2 (those of degrees $n = 14$ to 18 are reduced (multiplied) by a factor of 0.92, 0.78, 0.51, 0.23, 0.09). The spectrum (at Earth’s surface) of this spatially
Figure 6. First time derivative of the East component in the geomagnetic frame, $dY/dt$, resp. of the vertical component, $dZ/dt$, at the observatories Niemegk (NGK), Hermanus (HER), Kakioka (KAK) and Guam (GUA). Symbols refer to observations (annual difference of monthly means), whereas the solid curves indicate predicted values based on the models CHAOS (magenta), GRIMM (blue), CHAOS-2s (red) and CHAOS-2r (green). Versions of CHAOS-2 obtained without observatory data are shown by the dashed red, resp. green, curves.

filtered model is shown in Figure 3 by the red dashed curve. $dZ/dt$ at the core surface reveals a lot of details, but surprisingly the region of maximum signal is limited to the South Atlantic and Indian ocean, with maximum strength just west of South Africa. Again, the Pacific hemisphere is characterized by a very weak secular variation and less defined structures. The polar regions are also different, with larger scales and amplitudes in the Northern Polar Hemisphere, compared with the Southern one. This different dynamics in the core field temporal changes is reflected at the Earth’s surface by the different behavior of the magnetic pole motions (Korte and Mandea 2008).
Figure 7. Time series of $dZ/dt$ (annual differences of monthly means) at 400 km altitude, for the years 2001 - 2009. Values obtained from CHAMP satellite vector data (after removal of monthly estimates of the external field) are shown in black, predicted values of the CHAOS-2s model in red, and predicted values of the less regularized model CHAOS-2r in green. The left end-point of each curve corresponds to January 2001, whereas the right end-point corresponds to March 2009. The mean value was subtracted from each time series. Locations of the “virtual observatories” are shown by black dots. Polar regions have been excluded due to their strong contamination by ionospheric current systems.
Figure 8. First time derivative, $dZ/dt$, at the core surface in 2004.0 as given by the CHAOS-2s model. Coefficients of degree larger than 14 are damped. Contour interval is 5 $\mu$T/yr.

4 CONCLUSIONS

Using more than 10 years of continuous satellite data, augmented with monthly means from ground magnetic observatories, we have derived a new model, called CHAOS-2, of the static and time-varying part of Earth’s magnetic field. This model describes rapid core field variations occurring over only a few months.

Model predecessors and the data sets used to construct these models have been widely used to interpret rapid field variations by means of core flow (e.g., Holme and Olsen 2006; Olsen and Mandea 2007; Gillet et al. 2007; Pais and Jault 2008; Olsen and Mandea 2008). We hope that also the CHAOS-2 model described in this paper, which is significantly improved compared to earlier model versions, will be used by the scientific community. Model coefficients and data sets are available at www.space.dtu.dk/files/magnetic-models/CHAOS-2/.

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