DTU candidate field models for IGRF-12 and the CHAOS-5 geomagnetic field model

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Abstract

We present DTU’s candidate field models for IGRF-12 and the parent field model from which they were derived, CHAOS-5. Ten months of magnetic field observations from ESA’s Swarm mission, together with up-to-date ground observatory monthly means, were used to supplement the data sources previously used to construct CHAOS-4. The internal field part of CHAOS-5, from which our IGRF-12 candidate models were extracted, is time-dependent up to spherical harmonic degree 20 and involves sixth-order splines with a 0.5 year knot spacing. In CHAOS-5, compared with CHAOS-4, we update only the low-degree internal field model (degrees 1 to 24) and the associated external field model. The high-degree internal field (degrees 25 to 90) is taken from the same model CHAOS-4h, based on low-altitude CHAMP data, which was used in CHAOS-4.

We find that CHAOS-5 is able to consistently fit magnetic field data from six independent low Earth orbit satellites: Ørsted, CHAMP, SAC-C and the three Swarm satellites (A, B and C). It also adequately describes the secular variation measured at ground observatories. CHAOS-5 thus contributes to an initial validation of the quality of the Swarm magnetic data, in particular demonstrating that Huber weighted rms model residuals to Swarm vector field data are lower than those to Ørsted and CHAMP vector data (when either one or two star cameras were operating). CHAOS-5 shows three pulses of secular acceleration at the core surface over the past decade; the 2006 and 2009 pulses have previously been documented, but the 2013 pulse has only recently been identified. The spatial signature of the 2013 pulse at the core surface, under the Atlantic sector where it is strongest, is well correlated with the 2006 pulse, but anti-correlated with the 2009 pulse.

Keywords: Geomagnetism; Field modelling; IGRF; Swarm

Background

In May 2014, the IAGA task force responsible for IGRF-12 requested candidate geomagnetic reference field models [main field (MF) for epochs 2010.0, 2015.0 and predictive secular variation (SV) for 2015.0–2020.0] to be submitted by 1 October 2014. This article describes in detail the candidate models submitted by DTU Space and the time-dependent parent model from which they were derived, called CHAOS-5.

Geomagnetic field modellers producing candidate models for IGRF-12 were in the fortunate position that the European Space Agency (ESA) launched the Swarm satellite constellation, whose aim is to carry out the best ever survey of the Earth’s magnetic field, in November 2013.

In parallel with ongoing calibration and validation efforts, ESA promptly released L1b magnetic field data to the scientific community by May 2014. Swarm data were crucial to the DTU candidate models presented below. We therefore describe the selection, processing and modelling of the Swarm data in some detail. In addition to data from Swarm, we used data from previous satellite missions (Ørsted, CHAMP and SAC-C), along with ground observatory data kindly provided and checked by the British Geological Survey (Macmillan and Olsen 2013).

CHAOS-5, the parent model for the IGRF-12 candidates reported here, is the latest update of the CHAOS field model series (Olsen et al. 2006; Olsen et al. 2009; 2010; Olsen et al. 2014). The crucial aspects of this model are a time-dependent model of the large-scale internal field, a static model of the smaller-scale internal field, a parameterization of the large-scale external
field in both solar magnetic (SM) coordinates (with time-depen-
dependence parameterized by a disturbance index) and
geo-centric solar magnetospheric (GSM) coordinates, and
and a co-estimation of the Euler angles used for the rotation of
the three-component vector field from the magnetometer
frame to the star camera frame.

The main improvement of CHAOS-5 over CHAOS-4 is its
use of 10 months of Swarm data, as well as more recent
ground observatory data. The modelling technique and
data selection closely follow those previously described
by Olsen et al. (2014). CHAOS-5 is similar to the IGRF
parent models produced by a number of other teams (for
example Maus et al. 2010; Rother et al. 2013; Thomson
et al. 2010) in not explicitly modelling the ionospheric
field, in contrast to the more sophisticated comprehensive
modelling approach (Sabaka et al. 2015; Thébault et al.
2015). Instead, data selection for CHAOS-5 is limited to
dark-region data from geomagnetically quiet times (when
ionospheric currents are weak, at least at non-polar lati-
tudes), in an effort to isolate as best as possible the field of
internal origin.

In the ‘Data’ section, we provide more details con-
cerning the data selection and processing used in the
construction of CHAOS-5. The ‘Methods’ section gives a
brief description of our model parameterization, as well
as our chosen procedure for model estimation, including
the chosen temporal regularization. Differences between
CHAOS-5 and CHAOS-4 are summarized in Table 1.
Details concerning the extraction of the IGRF-12 can-
didate models are given in the section ‘Derivation of can-
didate models for IGRF-12’. In the ‘Results and discussion’
section, results from CHAOS-5 are presented, including
its fit to ground observatory and satellite data, and the
evolution of its model SV, which is, of course, relevant
regarding the predictive SV. The time evolution of the sec-
cular acceleration (SA) in CHAOS-5 is also described, and
an interesting new SA pulse at the core surface in 2013 is
documented.

Data
Satellite data
Dark-region data from geomagnetically quiet times, suit-
able for use within the CHAOS field modelling scheme,
have been selected. In particular, the following selection
criteria, previously used in the CHAOS-4 model (Olsen
et al. 2014), have again been employed:

1. Dark regions only (sun at least 10° below the horizon).
2. Strength of the magnetospheric ring current,
estimated using the RC index (Olsen et al. 2014), was
required to change by at most 2 nT/h.
3. Three vector components of the magnetic field were
taken for quasi-dipole (QD) latitudes equatorward of
±55°, while scalar field (intensity) data only were
used for higher QD latitudes or when attitude data
were not available.
4. Geomagnetic activity at non-polar latitudes
(equatorward of ±55° QD latitude) was sufficiently
low, such that the index Kp ≤ 2°.
5. Poleward of ±55° QD latitude, scalar data were only
selected when the merging electric field at the
magnetopause $E_m = 0.33v^{4/3}B_y^{2/3} \sin^{8/3}(|\Theta|/2)$,
where $v$ is the solar wind speed, $B_t = \sqrt{B_y^2 + B_z^2}$ is the
magnitude of the interplanetary magnetic field in the
y-z plane in GSM coordinates and
\[ \Theta = \arctan(B_y/B_z) \] (Newell et al. 2007), was
sufficiently small. More precisely, the weighted
average over the preceding 1 h, $E_{m,12} < 0.8$ mV/m.

All satellite data are further weighted proportional to
$\sin \theta$ (where $\theta$ is geographic co-latitude) to simulate an
equal-area distribution. The treatment and processing of
Ørsted, CHAMP and SAC-C data generally follow that
previously described for the CHAOS-4 field model (Olsen
et al. 2014). Figure 1 presents the total number of non-
polar magnetic satellite observations used each month in
deriving the low degree part of the CHAOS-5 model. Note
that because there are three Swarm satellites, and because
their data are selected in the same manner, there were a
relatively large number of data available since the launch
of Swarm in November 2013.

From ESA’s Swarm satellite trio, we used the operational
L1b data product Mag-L, for the 10 months 26 November
2013 to 25 September 2014, release 0302 when avail-
able, otherwise release 0301. Data were selected from the
three satellites, Swarm A, B and C at 60-s intervals unless
Flags_B=255 or Flags_q=255, which specifies non-valid
magnetometer or attitude data (see Olsen et al. 2013, for a
more detailed description of the L1b products and related
flags). We manually rejected Swarm A data from 29 to 30
January 2014 and 4 February 2014 as well as Swarm C data
from 25 to 26 March 2014 and 4, 8 and 11 April 2014 when
notably large outliers were identified, likely a result of spe-
cific manoeuvres that were carried out on these days. In
addition, gross outliers were excluded by requiring that
all vector field components be within 500 nT (and the
scalar field within 100 nT) of the predictions of a prelimi-
nary field model, CHAOS-4plus_V4, that we constructed
using the satellite and ground observatory data available in
August 2014. The Vector Field Magnetometer (VFM) data
were also slightly re-scaled, point-by-point isotropically
forcing their scalar value to agree with the Absolute Scalar
Magnetometer (ASM) data. This was a crude attempt to
make the ASM and VFM datasets more consistent, in
the absence of a suitable vector field correction at the
time of model determination in September 2014. Tests
showed that the impact of this scaling on magnetic field
### Table 1 Comparison of the CHAOS-4 and CHAOS-5 geomagnetic field models

|                           | CHAOS-4                      | CHAOS-5                      |
|---------------------------|------------------------------|------------------------------|
| **Data sources**          |                              |                              |
| Observatory monthly means | June 1997 - June 2013         | June 1997 - Sept 2014        |
| Ørsted vector             | March 1999 - Dec 2004         | March 1999 - Dec 2004        |
| SAC-C scalar              | Jan 2001 - Dec 2004           | Jan 2001 - Dec 2004          |
| CHAMP vector and scalar   | Aug 2000 - Sept 2010          | Aug 2000 - Sept 2010         |
| Swarm A vector and scalar | –                            | Nov 2013 - Sept 2014         |
| Swarm B vector and scalar | –                            | Nov 2013 - Sept 2014         |
| Swarm C vector and scalar | –                            | Nov 2013 - Sept 2014         |
| **Time-dependent internal field** |                              |                              |
| Model time span           | 1997.0–2013.5                | 1997.0–2015.0                |
| Spherical harmonic degree | \( n = 1–20 \)               | \( n = 1–20 \)               |
| Spline basis              | 6th order, 0.5 year knots     | 6th order, 0.5 year knots     |
| Based on                  | CHAOS-4i                     | CHAOS-5i                     |
| **Static internal field** |                              |                              |
| Spherical harmonic degree | \( n = 21–90 \)              | \( n = 21–90 \)              |
| Based on                  | CHAOS-4i (\( n = 21–24 \))   | CHAOS-5i (\( n = 21–24 \))   |
| and CHAOS-4h (\( n = 25–90 \)) |                        | and CHAOS-4h (\( n = 25–90 \)) |
| **External field**        |                              |                              |
| SM                        | \( n = 1:1 \text{ h, RC int + ext} \) | \( n = 1:1 \text{ h, RC int + ext} \) |
| 5 day \( \Delta q_0^i \), 30 day \( \Delta q_1^i \), \( \Delta s_1^i \) | \( n = 2: \text{ static} \) | \( n = 2: \text{ static} \) |
| GSM                       | \( n = 1–2, m = 0: \text{ static} \) | \( n = 1–2, m = 0: \text{ static} \) |
| **Euler angles**          |                              |                              |
| Ørsted                    | Before and after Jan 24 2000  | Before and after Jan 24 2000  |
| CHAMP                     | 10 day bins                  | 10 day bins                  |
| **Swarm**                 | –                            | 10 day bins                  |
| **Regularization**        |                              |                              |
| Spatial                   | Static field \( n > 85, < B_z^2 > \) | Static field \( n > 85, < B_z^2 > \) |
|                          | \( \lambda_0 = 1 \text{ nT}^{-2} \) | \( \lambda_0 = 1 \text{ nT}^{-2} \) |
| Temporal, interior        | \( < (dB_z^2/dr)^2 > \)     | \( < (dB_z^2/dr)^2 > \)     |
|                          | \( \lambda_3 = 0.33 \text{ (nT/year}^{-3})^{-2} \) | \( \lambda_3 = 0.33 \text{ (nT/year}^{-3})^{-2} \) |
|                          | \( \text{except } g_0^i, \lambda_3 = 10 \text{ (nT/year}^{-3})^{-2} \) | \( \text{except } m = 0, \lambda_3 = 100 \text{ (nT/year}^{-3})^{-2} \) |
| Temporal, endpoints       | \( < (dB_z^2/dr)^2 > \)     | \( < (dB_z^2/dr)^2 > \)     |
|                          | \( \lambda_2 = 10 \text{ (nT/year}^{-2})^{-2} \) | \( \lambda_2 = 100 \text{ (nT/year}^{-2})^{-2} \) |

Contributing data, model parameterization and model regularization are presented. Improvements of CHAOS-5 compared to CHAOS-4 are shown in bold. \(< >\) indicates integration over the core-mantle boundary.

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models was however small, in part because data from sunlit regions (which have larger ASM-VFM differences, see Lesur et al. 2015) were not selected. At polar latitudes, only ASM scalar data were used. In all, we used 3 × 53, 137 (17,485) vector data (scalar data) from Swarm A, 3 × 53, 253 (17,744) from Swarm B and 3 × 49, 984 (16,697) from Swarm C, respectively. The altitude of the three Swarm satellites versus time and the coverage of the selected data as a function of latitude and time are presented in Fig. 2.

**Observatory data**

Annual differences of revised observatory monthly means (Olsen et al. 2014) for the time interval January 1997 to September 2014 were used as additional observational constraints on the SV. Revised monthly means were
derived from the hourly mean values of 159 observatories (locations shown in Fig. 3) which have been carefully checked for trends, spikes and other errors (Macmillan and Olsen 2013). The observatory data were rotated from geodetic to geographic components. Prior to producing monthly means by a robust method based on Huber weights (Huber 1964), we removed estimates of the ionospheric (plus induced) field as predicted by the CM4 model (Sabaka et al. 2004) and the large-scale magnetospheric (plus induced) field, as predicted by the preliminary field model CHAOS-4plus_V4. After taking annual differences, this resulted in 21,733 values of the first time derivative of the vector field components, $dB_r/dt, dB_θ/dt, dB_φ/dt$ with the distribution in time.

Fig. 1 Total number of non-polar satellite data (stacked histogram) used in the derivation of the low degree part of the CHAOS-5 model versus time

Fig. 2 Daily mean altitude of the three Swarm satellites (left) and the geographic latitude coverage versus time of the Swarm vector and scalar data used in the low degree part of the CHAOS-5 model (right)
shown in the bottom panel of Fig. 3. We emphasize that CM4-based estimates of the ionospheric field were removed only from the hourly mean observatory data during the derivation of revised monthly means (since data from all local times were used) and they were not removed from the dark-region satellite data used.

Methods
Model parameterization
The parametrization of the CHAOS-5 field model follows closely that of previous versions in the CHAOS model series (Olsen et al. 2006, 2009, 2010, 2014). We assume measurements take place in a region free from electric currents, in which case the vector magnetic field \( \mathbf{B} \) may be described by a potential such that \( \mathbf{B} = -\nabla V \). The magnetic scalar potential \( V = V^{\text{int}} + V^{\text{ext}} \) consists of \( V^{\text{int}} \), describing internal (core and lithospheric) sources, and \( V^{\text{ext}} \), describing external (mainly magnetospheric) sources and their Earth-induced counterparts. Both internal and external parts are expanded in spherical harmonics. The CHAOS-5 model thus consists of spherical harmonic coefficients together with sets of Euler angles needed to rotate the satellite vector field readings from the magnetometer frame to the star camera frame.

Considering first the internal field, we work in an Earth-centred Earth-fixed (ECEF) coordinate system using a spherical harmonic expansion

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

(1)
where $a = 6371.2$ km is a reference radius, $(r, \theta, \phi)$ are geographic spherical polar coordinates, $P^m_n(\cos \theta)$ are the Schmidt semi-normalized associated Legendre functions, $\{g^m_n, h^m_n\}$ are the Gauss coefficients describing internal sources, and $N_{\text{int}}$ is the maximum degree and order of the internal expansion. The internal coefficients $\{g^m_n(t), h^m_n(t)\}$ up to $n = 20$ are time-dependent; this dependence is described by order 6 B-splines (De Boor 2001) with a 6-month knot separation and fivefold knots at the endpoints $t = 1997.0$ and $t = 2015.0$. Internal coefficients for degrees 21 and above are static, and a maximum degree of 80 was used during the derivation of the new model for the low degree field (CHAOS-5l, where 'l' denotes low degrees) described here.

Regarding the external field, we represent the near magnetospheric sources, e.g. magnetospheric ring current, by a spherical harmonic expansion in solar magnetic (SM) coordinates (up to $n = 2$, with a special treatment of the $n = 1$ terms). Regarding remote magnetospheric sources, e.g. magnetotail and magnetopause currents, we use a spherical harmonic expansion in geocentric solar magnetospheric (GSM) coordinates (also up to $n = 2$, but restricted to order $m = 0$):

$$V^{\text{ext}} = a^2 \sum_{n=1}^{n} \sum_{m=0}^{m} (g^m_n \cos mT_d + s^m_n \sin mT_d) \left( \frac{r}{\rho} \right)^n P^m_n(\cos \theta_d)$$

$$+ a \sum_{n=1}^{n} q^0_n \cos \phi$$

(2)

where $\theta_d$ and $T_d$ are dipole co-latitude and dipole local time. The degree-1 coefficients in SM coordinates are time-dependent and are further expanded as

$$q^0(t) = \hat{q}^0_1 \left[ \epsilon(t) + i(t) \left( \frac{a}{\rho} \right)^3 \right] + \Delta q^0_1(t)$$

(3a)

$$q^1_1(t) = \hat{q}^1_1 \left[ \epsilon(t) + i(t) \left( \frac{a}{\rho} \right)^3 \right] + \Delta q^1_1(t)$$

(3b)

$$s^1_1(t) = \hat{s}^1_1 \left[ \epsilon(t) + i(t) \left( \frac{a}{\rho} \right)^3 \right] + \Delta s^1_1(t)$$

(3c)

where the terms in brackets describe the contributions from the magnetospheric ring current and its Earth-induced counterpart as estimated by the RC index (Olsen et al. 2014), $\epsilon(t) = \epsilon(t) + i(t)$. We co-estimate the time-independent regression factors $\hat{q}^0_1, \hat{q}^1_1, \hat{s}^1_1$ and the time-varying ‘RC baseline corrections’ $\Delta q^0_1, \Delta q^1_1, \Delta s^1_1$ in bins of 5 days (for $\Delta q^0_1$) and 30 days (for $\Delta q^1_1, \Delta s^1_1$), respectively. These allow for differences between the ground-based estimate of the degree 1 external magnetic signal (the RC index) and that inferred from low Earth orbit satellites.

In addition to the above spherical harmonic coefficients, we co-estimate the Euler angles describing the rotation between the vector magnetometer frame and the star camera frame. For Ørsted, this yields two sets of Euler angles (one for the period before 24 January 2000 when the onboard software of the star camera was updated and one for the period after that date), while for CHAMP and each Swarm satellite, we solve for Euler angles in bins of 10 days.

The new model described here, derived specifically to produce candidate models for IGRF-12, is essentially an update of the model CHAOS-4l including 10 months of Swarm data and the latest annual differences of observatory revised month means. We refer to this new parent model as CHAOS-5l. It involves time-dependent terms (for degrees $n = 1–20, 18,040$ coefficients) and static terms (for $n = 21–80, 6120$ coefficients) together resulting in a total of 24,160 internal Gauss coefficients. The total number of external field parameters is 1301, which is the sum of 5 SM terms ($q^m_n, s^m_n$ for $n = 2$), 3 RC regression coefficients $q^0_1, q^1_1, s^1_1$, 2 GSM coefficients ($q^0_n, q^2_n$), 949 baseline corrections $\Delta q^0_1$ and 2 $\times$ 171 baseline corrections $\Delta q^1_1, \Delta s^1_1$. Considering the Euler angles for the Ørsted, CHAMP and the Swarm satellites yields an additional $3 \times (2 + 366 + 94) = 1386$ model parameters. This finally results in a total of 24,160 + 1301 + 1386 = 26,847 model parameters to be estimated.

Model estimation and regularization

The model parameters described above for CHAOS-5l were estimated from 753,996 scalar data and 3 $\times$ 741,440 vector data by means of a regularized iteratively reweighted least-squares algorithm using Huber weights, minimizing the cost function

$$e^T C^{-1} e + \lambda_3 m^T \Lambda_3 m + \lambda_2 m^T \Lambda_2 m$$

(4)

where $m$ is the model vector, the residual vector $e = d_{\text{obs}} - d_{\text{mod}}$ is the difference between the vector of observations $d_{\text{obs}}$ and the vector of model predictions $d_{\text{mod}}$, and $C$ is the data error covariance matrix. In the data error covariance matrix $C$, anisotropic errors due to attitude uncertainty (Holme and Bloxham 1996) are considered for the vector field satellite data. A priori data error variances for the scalar field were assumed to be 2.5 nT for Ørsted and 2.2 nT for CHAMP and Swarm, while the attitude uncertainties were allocated as in CHAOS-4 (Olsen et al. 2014), but with a pointing uncertainty of 10 arc sec for Swarm vector field data.

$\Lambda_3$ and $\Lambda_2$ are block diagonal regularization matrices penalizing the squared values of the third and second, respectively, time derivatives of the radial field $B_r$. 


at the core surface. $\Delta t_3$ involves integration over the full timespan of the model, while $\Delta t_2$ involves evaluating the second time derivative only at the model endpoints $t = 1997.0$ and 2015.0. The parameters $\lambda_3$ and $\lambda_2$ control the strength of the regularization applied to the model time dependence during the entire modelled interval and at the endpoints, respectively. We tested several values for these parameters and finally selected $\lambda_3 = 0.33$ (nT/year$^3$)$^{-2}$ (the same as used in CHAOS-4l) and $\lambda_2 = 100$ (nT/year$^2$)$^{-2}$ (a stronger endpoint constraint than used in CHAOS-4l). In addition, all zonal terms were treated separately (in CHAOS-4l, only the axial dipole was treated separately), with $\lambda_3$ increased to 100 (nT/year$^3$)$^{-2}$, since we found these internal field components were more strongly perturbed by (i) unmodelled external field fluctuations and (ii) shortcomings in the data coverage due to lack of data in the summer polar region. The regularization parameters were chosen following a series of experiments, primarily relying on comparisons to the SV recorded at ground observatories.

Since both scalar data and Huber weights are involved, the cost function depends nonlinearly on the model parameters. The solution to the minimization problem was therefore obtained iteratively using a Newton-type algorithm. The starting model was a single epoch model with linear SV centred on 2010.0. The final model was obtained after six iterations, by which point sufficient convergence was obtained with the rms misfit converging to better than 0.01 nT and the Euclidean norm of the model change in the final iteration less than 0.005 % that of the model itself.

The complete CHAOS-5 field model was obtained in a final step by combining the spherical harmonic coefficients of new model CHAOS-5l with the previous CHAOS-4h model (Olsen et al. 2014), which in September 2014 was our best model for the high-degree lithospheric field. The transition between these models was implemented at $n = 24$ as for CHAOS-4. The various differences between CHAOS-5 and CHAOS-4 are collected for reference in Table 1. Note that the model statistics reported below are those for CHAOS-5l, the parent model from which our IGRF-12 candidate models were extracted.

**Derivation of candidate models for IGRF-12**

IGRF-12 candidates were extracted from the parent model CHAOS-5l as follows:

- **DGRF, epoch 2010.0**
  The parent model CHAOS-5l, with its spline-based time dependence was evaluated at epoch 2010.0, and the internal spherical harmonic coefficients up to degree and order 13 output to 0.01 nT.

- **IGRF, epoch 2015.0**

The parent model CHAOS-5l, with its spline-based time dependence was evaluated at epoch 2014.75, the end of the month when the last input satellite data were available to constrain the model. The resulting coefficients were then propagated forward to epoch 2015.0, using the linear SV evaluated from CHAOS-5l in epoch 2014.0 (as in our SV candidate, to avoid spline model end-effects) as follows:

$$g_n^m(t = 2015.0) = g_n^m(t = 2014.75) + 0.25 \cdot \dot{g}_n^m(t = 2014.0)$$

Here $g_n^m$ represents each of the Gauss coefficients $\{g_n^m, h_n^m\}$, while $\dot{g}_n^m$ represents the SV coefficients $\{\dot{g}_n^m, \dot{h}_n^m\}$ in nT/year. The resulting internal spherical harmonic coefficients for the internal field in epoch 2015.0 up to degree and order 13 were output to 0.01 nT.

- **Predicted average SV, 2015.0 to 2020.0**
  Since there can be spline model end-effects in the secular acceleration (SA), we evaluated the SV from CHAOS-5l at epoch 2014.0, rather than in 2015.0, and did not attempt any extrapolation. These end-effects are essentially due to the lack of ‘future’ data for constraining the SV and SA at the model endpoint, and because SV estimates based on annual differences of ground observatory monthly means are available only up to 6 months before the latest available ground observatory data. It should also be noted that the SV in a spline-based model such CHAOS-5l at a particular epoch is not the true instantaneous SV, but a weighted time average, with the amount of time averaging varying with spherical harmonic degree according to the imposed regularization.
  The SV spherical harmonic coefficients (first time derivative of the spline model) for the internal field in epoch 2014.0, up to degree and order 8, were then output to 0.01 nT/year. We also provided SV predictions to degree and order 13 as a test secular variation model.

No uncertainty estimates were provided with our candidate models, since we are unable to calculate satisfactory estimates. The largest errors are likely biases caused by unmodelled sources (Sabaka et al. 2015) which cannot be assessed using a formal model error covariance matrix, or by constructing models using the same technique from independent datasets.

**Results and discussion**

**Fit to satellite data**

Statistics for the misfit between the CHAOS-5l parent field model and the observations used to derive it are collected in Table 2, using the $(B_R, B_L, B_Z)$ notation of Olsen (2002) that is relevant when describing anisotropic
pointing errors. The weighted rms misfits to the Ørsted, CHAMP and SAC-C data are similar to those found previously for CHAOS-4l. Regarding the Swarm data, the Huber weighted rms misfits to scalar intensity data \( (F_{\text{nonpolar}} + B_B) \) of 2.09 nT for Swarm A, 2.07 nT for Swarm B and 2.09 nT for Swarm C are very similar to that found for the CHAMP data, 2.07 nT, considering all 10 years of operation. However, the misfit to the other two vector field components \((B_L \text{ and } B_3)\) was approximately 0.5 nT lower for Swarm data compared to CHAMP data (note the distinction between \(B_L\) and \(B_3\) is arbitrary for Swarm, while CHAMP data with either one or two star cameras operating have been considered). This difference mapped into lower misfits to Swarm data in the \(B_r\) and \(B_\phi\) geographic components (e.g. the Huber weighted rms misfit for \(B_r\) was 2.77 nT for CHAMP compared to 1.83 nT, 1.99 nT and 1.93 nT for Swarm A, B and C, respectively).

The residuals between CHAOS-5l and the Swarm magnetic field data show the expected trends as function of geomagnetic latitude (see Fig. 4, left panel), with the scalar residuals being much larger in the polar region and minimum close to \(\pm 35^\circ\) geomagnetic latitude, where the perturbations due to unmodelled ring current fluctuations are perpendicular to the dipole-dominated main field. The Huber weighted residuals as a function of time for Swarm A, B and C at this geomagnetic latitude (\(\pm 35^\circ\)) are presented in Fig. 4, right panel. Residuals are usually less than \(\pm 5\) nT for all three satellites at this location, with similar trends seen for each satellite.

### Fit to observatory monthly means

The fit of CHAOS-5l to annual differences of observatory monthly means is similar to that obtained for the previous CHAOS-4l model, with the rms Huber weighted misfits for \(dB_r/\text{dt}\), \(dB_\phi/\text{dt}\) and \(dB_\theta/\text{dt}\) of 3.91, 3.83 and 3.12 nT/year, respectively. Examples of comparisons between the SV predicted by CHAOS-5l and SV estimates from annual differences of monthly means at selected observatories are presented in Fig. 5. CHAOS-5l succeeds in reproducing the SV trends on timescales of 2 years and longer at these observatories. The SV obtained from CHAOS-5l thus appears reasonable, at least up to the time of the latest available observatory SV estimates, from early 2014 (using annual differences of monthly means up to August 2014). There is a clear improvement in the SV predicted by the CHAOS-5 compared to that predicted by CHAOS-4 in 2013 and 2014 (e.g. \(dB_r/\text{dt}\) at HER, \(dB_\phi/\text{dt}\) at NGK, KAK, \(dB_\theta/\text{dt}\) at HON, HER).

### Time dependence of secular variation coefficients

The time evolution of the SV in CHAOS-5l for degrees 1 to 8 is presented in Fig. 6, 7 and 8, with the SV from CHAOS-4l again shown for reference. The two models agree well until approximately 2013, after which the SV

| Data | Component | \(N\) | CHAOS-5l Mean | CHAOS-5l rms |
|------|-----------|------|--------------|--------------|
| Ørsted | \(F_{\text{polar}}\) | 121,293 | 0.46 | 3.44 |
| | \(F_{\text{nonpolar}} + B_B\) | 367,713 | 0.16 | 2.37 |
| | \(B_L\) | 87,672 | -0.05 | 7.37 |
| | \(B_3\) | 87,672 | 0.15 | 3.35 |
| | \(B_r\) | 87,672 | 0.13 | 4.47 |
| | \(B_\theta\) | 87,672 | 0.23 | 5.36 |
| | \(B_\phi\) | 87,672 | 0.00 | 5.03 |
| CHAMP | \(F_{\text{polar}}\) | 188,015 | -0.37 | 4.90 |
| | \(F_{\text{nonpolar}} + B_B\) | 497,394 | -0.09 | 2.07 |
| | \(B_L\) | 497,394 | -0.02 | 3.30 |
| | \(B_3\) | 497,394 | 0.07 | 3.42 |
| | \(B_r\) | 497,394 | 0.02 | 2.77 |
| | \(B_\theta\) | 497,394 | 0.10 | 3.56 |
| | \(B_\phi\) | 497,394 | -0.01 | 2.71 |
| SAC-C | \(F_{\text{polar}}\) | 26,118 | 0.43 | 3.78 |
| | \(F_{\text{nonpolar}}\) | 86,603 | 0.40 | 2.72 |
| Swarm A | \(F_{\text{polar}}\) | 17,485 | -0.03 | 3.80 |
| | \(F_{\text{nonpolar}} + B_B\) | 53,137 | -0.01 | 2.09 |
| | \(B_L\) | 53,137 | -0.05 | 2.79 |
| | \(B_3\) | 53,137 | 0.05 | 2.72 |
| | \(B_r\) | 53,137 | -0.01 | 1.83 |
| | \(B_\theta\) | 53,137 | 0.18 | 2.95 |
| | \(B_\phi\) | 53,137 | -0.16 | 2.69 |
| Swarm B | \(F_{\text{polar}}\) | 17,774 | 0.15 | 3.65 |
| | \(F_{\text{nonpolar}} + B_B\) | 53,253 | -0.06 | 2.07 |
| | \(B_L\) | 53,253 | -0.03 | 2.80 |
| | \(B_3\) | 53,253 | 0.08 | 2.84 |
| | \(B_r\) | 53,253 | 0.02 | 1.99 |
| | \(B_\theta\) | 53,253 | 0.22 | 3.00 |
| | \(B_\phi\) | 53,253 | -0.13 | 2.71 |
| Swarm C | \(F_{\text{polar}}\) | 16,697 | 0.13 | 3.82 |
| | \(F_{\text{nonpolar}} + B_B\) | 49,984 | 0.05 | 2.09 |
| | \(B_L\) | 49,984 | -0.05 | 2.80 |
| | \(B_3\) | 49,984 | 0.04 | 2.80 |
| | \(B_r\) | 49,984 | 0.02 | 1.93 |
| | \(B_\theta\) | 49,984 | 0.11 | 3.00 |
| | \(B_\phi\) | 49,984 | -0.15 | 2.71 |
| Observatory | \(dB_r/\text{dt}\) | 21,733 | 0.13 | 3.91 |
| | \(dB_\phi/\text{dt}\) | 21,733 | -0.02 | 3.83 |
| | \(dB_\theta/\text{dt}\) | 21,733 | -0.00 | 3.12 |

Statistics for the vector components are given both in the coordinate system \((B_r, B_\theta, B_\phi)\) that is defined by the bore-sight of the star camera and the ambient field direction (cf. Olsen et al. 2000) and also in the standard geographic (ECEF) frame \((r, \theta, \phi)\).
from CHAOS-4l diverges from that of CHAOS-5l, particularly in the lowest degrees which were least regularized. Note that penalization of SA at the model endpoints was imposed more strongly in CHAOS-5l; hence, its SV is close to constant near the ends of the model timespan. In addition, the zonal terms \((m = 0)\), which sometimes showed spurious SV trends close to the endpoints in CHAOS-4 (e.g. in \(\frac{dg_m^0}{dt}, \frac{dg_m^2}{dt}\)) were damped more heavily in CHAOS-5l.

**Spectral properties of DTU IGRF-12 candidate models**

The power spectra of the DTU candidate MF and SV models for IGRF-12 are presented in Fig. 9, along with spectra of comparable models from IGRF-11, the MF in 2010.0, and the predicted SV for 2015.0 to 2020.0. The spectra of our IGRF-12 MF candidates are very similar to those of the IGRF-11 MF in 2010.0. The spectrum of the difference between our DGRF-2010 candidate and IGRF-2015 candidate, divided by 5 to get a change per year, is also very close to the spectrum of the predicted SV for 2010.0 to 2015.0 from IGRF-11 (Finlay et al. 2010). In comparison, the spectrum of our new SV candidate for 2015.0 to 2020.0 contains slightly more power at degrees 3 to 5, but is otherwise similar.

**Rationale for choice of SV candidate**

The construction and evaluation of SV candidates have long been considered the most challenging aspects of producing a new IGRF generation (Lowes 2000). Here, we derived our IGRF-12 SV candidate taking the position that it is not yet possible to reliably predict future SA events (for example related to geomagnetic jerks) since prognostic forward models capturing the relevant core physics on short time scales are not yet available. We therefore take our estimate of the current SV to be our prediction of the SV for 2015.0 to 2020.0, essentially assuming no average SA or equivalently that the SA will average to zero over the upcoming 5 years. As discussed above, we take the SV from 2014.0 in our spline model as our estimate of the present SV, to avoid problems related to spline model end-effects.

**Secular acceleration pulses in 2006, 2009 and 2013**

Pulses of SA at the core surface have been identified in the past decade (Chulliat et al. 2010), primarily using data collected by the CHAMP satellite. They are thought to underlie localized rapid secular variation events observed at the Earth’s surface (Lesur et al. 2008; Olsen and Mandea 2008) and the well-known geomagnetic jerks seen in ground observatory data (Chulliat et al. 2010). Previous studies have highlighted two pulses in 2006 and 2009 in opposite directions (Chulliat and Maus 2014; Olsen et al. 2014). These SA pulses are clearly evident when plotting the time evolution of the SA power integrated over the core surface, as given by

\[
S_A = \sum_{n=1}^{N_{SA}} (n+1) \left( \frac{c}{a} \right)^{2n+4} \sum_m \left( \frac{\tilde{g}_m^n}{\tilde{h}_m^n} \right)^2 + \left( \frac{\tilde{h}_m^n}{\tilde{g}_m^n} \right)^2, \tag{6}
\]

for example, as shown in Fig 10. Here, we take \(c = 3480\) km to be the radius of the core surface, \(\tilde{g}_m^n, \tilde{h}_m^n\) are the Gauss coefficients for the SA, evaluated from the sixth-order spline model, and we have chosen the degree of truncation \(N_{SA} = 8\), to reflect those degrees in which we see well-resolved time dependence of the SV. In Fig 10, we plot \(S_A(t)\) from both CHAOS-4 and the new CHAOS-5 model.
Fig. 5 Annual differences of observatory revised monthly means (black dots) compared to the SV predictions from CHAOS-5l (solid red line), those from CHAOS-4l (green dashed line) and for the DTU SV candidate for IGRF-12 (blue circle, shown in 2015.0). For selected observatories, with locations marked in red in Fig. 3, arranged by geographic latitude and with field components rotated to the geomagnetic dipole frame.
Fig. 6 Time dependence of the first 27 spherical harmonic coefficients ($\Delta f_j^l / \Delta t$ to $\Delta h_j^l / \Delta t$) of the secular variation from CHAOS-6 (solid red line) with CHAOS-4 (green dashed line) also shown for reference. The blue circle denotes the DTU SV-2015-2020 candidate model in 2015.0.
Fig. 7 Time dependence of the next 27 spherical harmonic coefficients ($d \phi^j_l / dt$ to $d \phi^j_l / dt$) of the secular variation from CHAOS-5l (solid red line) with CHAOS-4l (green dashed line) also shown for reference. The blue circle denotes the DTU SV-2015-2020 candidate model in 2015.0
Fig. 8 Time dependence of the next 26 spherical harmonic coefficients (from $dh_{37}/dt$ to $dh_{88}/dt$) of the secular variation from CHAOS-5I (solid red line) with CHAOS-4I (green dashed line) also shown for reference. The blue circle denotes the DTU SV-2015-2020 candidate model in 2015.0
They agree rather well up until 2011, although we find slightly more SA power in the 2009 pulse in CHAOS-5. The major difference between CHAOS-4 and CHAOS-5 is a strong SA pulse seen in 2013 in CHAOS-5. There was possibly already weak evidence for a pulse around 2013 in CHAOS-4, but the sparsity of satellite data in this model after 2010, and the closeness of the pulse to the model endpoint, made interpretation of this feature difficult. Evidence for the 2013 pulse was first presented at the third Swarm Science Meeting (Copenhagen, June 2014) by two independent teams. Chulliat, Alken and Maus (see Chulliat et al. 2015) highlighted evidence derived from DMSP satellite data, while the present authors showed results from a preliminary version of CHAOS-5.
Fig. 11 Secular acceleration (SA) at the core surface (degrees 1 to 8 only) in 2006.2 (top), 2009.2 (middle) and 2012.9 (bottom). Maps are in Hammer-Aitoff projection, units are microtesla per year$^2$ ($\mu$T/year$^2$).
Chulliat and Maus (2014) pointed out that the dominant signatures of the 2006 and 2009 pulses in the radial SA at the core-mantle boundary, found in the low-latitude Atlantic sector, are essentially anti-correlated. In CHAOS-5, we find that for the new pulse in 2013, the radial SA signature in the Atlantic sector is again correlated with the 2006 pulse and anti-correlated with the 2009 pulse, as shown in Fig. 11. A detailed discussion of this point, and corroborating evidence obtained from the DMSP satellites, is given by Chulliat et al. (2015).

A striking example of the oscillatory core surface SV that now requires an explanation is that the strongest feature in the radial SA under the eastern edge of Brazil was negative in 2006, positive in 2009 and negative again in 2013. Gillet et al. (2015) have proposed that such events can be explained by oscillations in the non-zonal (i.e. non-axisymmetric) part of the azimuthal (east-west) quasi-geostrophic core flow at low latitudes. Chulliat et al. (2015) suggest an alternative idea that fast equatorial MHD waves in a stratified layer at the top of the core may be responsible. The identification of the 2013 pulse in CHAOS-5 opens the door to further detailed study of such hypotheses. The occurrence of SA pulses in 2006.2, 2009.2 and 2013.9 also leads us to wonder whether the next pulse, expected to have the same polarity as the 2009 event, might occur around 2016, before the end of the nominal Swarm mission. Since Swarm should be providing high-quality magnetic field measurements with unprecedented space-time coverage throughout this period, it promises to be an exciting opportunity to characterize a SA pulse in great detail.

Conclusions

We have presented the CHAOS-5 geomagnetic field model, including the parent model CHAOS-5l from which DTU’s candidate field models for IGRF-12 were derived. Details of the magnetic data used to construct CHAOS-5 (including their selection and processing) have been documented, with a focus on data from ESA’s Swarm satellite constellation. The CHAOS-5 model parameterization and estimation scheme has been reported, and details given concerning how the candidate field models for IGRF-12 were extracted.

We find acceptable misfits of CHAOS-5 to both ground observatory and Swarm data in 2014, and no evidence of unreasonable model oscillations or spurious trends. CHAOS-5 thus provides a consistent representation of magnetic data from six independent satellites (Ørsted, CHAMP, SAC-C and Swarm A, B, C), as well as ground observatory data, between 1999 and 2015. The Huber weighted rms misfit of the CHAOS-5 model to the Swarm vector field data is found to be lower than the Huber weighted rms misfit to the Ørsted and CHAMP vector field data (where either 1 or 2 star cameras were operating), for example considering the radial field component, Huber weighted rms misfits of 1.83, 1.99 and 1.93 nT to Swarm A, B, C data were obtained, compared to 2.77 nT for CHAMP. Overall, the Swarm data seems very well suited for geomagnetic field modelling, and we had no hesitation in using field models based on Swarm L1b magnetic field data, version 0301/0302, to construct our IGRF-12 candidate models.

CHAOS-5 provides evidence of a secular acceleration pulse around 2013 at the core surface. The amplitude of this new 2013 pulse appears to be larger than the 2009 pulse, and in the Atlantic sector of the core surface, its spatial pattern is well correlated to the 2006 pulse and anti-correlated to 2009 pulse (see also Chulliat et al. 2015). If another pulse happens around 2016, then Swarm will be ideally placed to provide a much more detailed characterization of this presently poorly understood phenomenon.

The CHAOS-5 model, as well as the Matlab software to evaluate it, is available from www.spacecenter.dk/files/magnetic-models/CHAOS-5/.

Competing interests

The authors declare they have no competing interests.

Authors’ contributions

CCF derived the CHAOS-5 field model, extracted the IGRF-12 candidate models, and drafted the manuscript. NO developed the CHAOS field modelling software and participated in the design of the study. LTC carried out preparation and pre-processing of Ørsted and Swarm data. All authors read and approved the final manuscript.

Acknowledgements

We wish to thank Benoit Langlais, an anonymous reviewer, and the guest editor Erwan Thébault for constructive comments that helped us to improve the manuscript. ESA is thanked for providing prompt access to the Swarm L1b data. The staff of the geomagnetic observatories and INTERMAGNET are thanked for supplying high-quality observatory data, and BGS is thanked for providing us with checked and corrected observatory hourly mean values. The support of the CHAMP mission by the German Aerospace Center (DLR) and the Federal Ministry of Education and Research is gratefully acknowledged. The Ørsted Project was made possible by extensive support from the Danish Government, NASA, ESA, CNES, DARA and the Thomas B. Thriges Foundation. Support for CCF by the Research Council of Norway through the Petromaks programme, by ConocoPhillips and Lundin Norway, and by the Technical University of Denmark is highly appreciated.

Received: 10 February 2015 Accepted: 15 June 2015
Published online: 22 July 2015

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