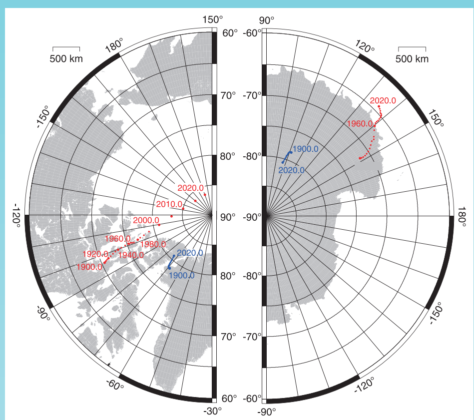
Earth, Planets and Space

International Geomagnetic Reference Field - The Twelfth generation



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PREFACE **Open Access**

Special issue "International Geomagnetic Reference Field—the twelfth generation"

E. Thébault[1*], CC Finlay[2] and H. Toh[3]

This special issue of Earth, Planets and Space, synthesizes the efforts made during the construction of the twelfth generation of the International Geomagnetic Reference Field (IGRF-12) that was released online in December 2014 (http://www.ngdc.noaa.gov/IAGA/vmod/igrf.html). The IGRF-12 is a series of standard mathematical models describing the large scale internal part of the Earth's magnetic field between epochs 1900.0 and 2015.0 with a forecast to epoch 2020.0. This activity has been maintained since 1968 by a working group of volunteer scientists from several international institutions but grew out from discussions started in the early 1960s (Barton, 1997). The IGRF task force operates under the auspices of the International Association of Geomagnetism and Aeronomy/Association Internationale de Géomagnétisme et d'Aéronomie (IAGA/AIGA), which is one of the International Union of Geodesy and Geophysics/Union Internationale de Géodésie et Géophysique (IUGG/UIGG), an "international organization dedicated to advancing, promoting, and communicating knowledge of the Earth system, its space environment, and the dynamical processes causing change" (http://www.iugg.org/).

The twelfth generation of IGRF models extends and updates the previous one (the IGRF-11, Finlay et al. 2010). It provides a new Definitive Geomagnetic Reference Field model for epoch 2010.0. It proposes a provisional reference field model for epoch 2015.0 and a predictive part for epochs ranging from 2015.0 to 2020.0 (Thébault et al. 2015a). These models were derived from candidate models submitted by 10 teams. The teams were led by the British Geological Survey (UK), DTU Space (Denmark), ISTerre (France), IZMIRAN (Russia), NOAA/NGDC (USA), GFZ Potsdam (Germany), NASA/GSFC (USA), IPGP (France), LPG Nantes (France), and ETH Zurich (Switzerland). Modelers made use of the data measured at ground geomagnetic observatories and built their models using satellite data from the German satellite CHAMP (2000–2010), the Danish satellite Ørsted (1999-), the Argentine-US-Danish satellite SAC-C (2001–2013), and most importantly for the new 2015 model, the European Swarm constellation (launched in November 2013; https://earth.esa.int/web/guest/missions/esa-operational-eo-missions/swarm; see also, Friis-Christensen and Floberghagen, 2013). The teams adopted independent data selection, processing, and modeling procedures whose details can be found in the papers appearing in this special issue. Some teams derived their candidate models from a parent model (Finlay et al. 2015; Gillet et al. 2015; Hamilton et al. 2015; Sabaka et al. 2015). The parent model parameterizations are more complex in space and in time than IGRF models. They are primarily derived for scientific purposes and include co-estimation of various internal and external source fields. The candidate models to IGRF were subsequently estimated from the parent models by selecting the internal field contribution at the epoch and to a spatial resolution requested by the call for IGRF-12. Other teams focused their effort on deriving directly a model closely meeting the IGRF specifications (Alken et al. 2015, Lesur et al. 2015; Saturnino et al. 2015; Vigneron et al. 2015). They relied on data selected within time windows centered on the epochs of interest. This sometimes involved drastic data selection and preprocessing to separate empirically the various source fields. In general, all models relied on statistical weighting schemes to down-weight measurements poorly fit by the model and were directly expanded in spherical harmonics, with the exception of the candidate models derived by the IZMIRAN team (Petrov et al. unpublished) which relied on a principal component analysis of the data that was then converted into spherical harmonics. IGRF-12 also contains a predictive estimate for the secular variation that covers the epochs 2015–2020. Teams submitted prediction candidates derived using both "physical" and "mathematical" approaches. The "mathematical" models were built by teams relying on analytical extrapolation and who assumed that the magnetic field will evolve linearly over the next 5 years

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(e.g., Alken et al. 2015; Finlay et al. 2015; Lesur et al. 2015; Saturnino et al. 2015). The "physical" models were proposed by teams who considered that forecasting the chaotic geodynamo although difficult is numerically and statistically achievable. Two teams applied the tools of geophysical assimilation (Fournier et al. 2015, Kuang et al. unpublished), and two others explored a priori statistical hypotheses on the core flow (Gillet et al. 2015; Hamilton et al. 2015). These physically motivated models are not only attractive for forecasting the Earth's magnetic field but also for hindcasting it at past epochs poorly constrained by the available magnetic field measurements. In IGRF-12, the term "definitive", which concerns models from 1900.0 to 2010.0, is used because substantial improvement is currently unlikely. Future retrospective analyses and improvements of these models might be achieved by data reprocessing, of course. For instance, Stockman et al. (2015) propose a new calibration of the POGO satellite measurements for the late 1960s. However, the systematic revision of the IGRF models for epochs earlier than 2010.0 will be more likely conceivable when our understanding about the physics of Earth's magnetic field is sufficient to include more realistic prior information in geomagnetic field models. Each candidate model to the IGRF model was evaluated in order to inform the construction of the IGRF-12 model. The variety of techniques applied amongst the candidate models often complicated the work of the evaluators but, after some debate, all submitted models were included in the derivation of the final IGRF-12 via a robust weighting scheme applied in space. The evaluation procedure and the applied diagnostic tests are documented in Thébault et al. (2015b). Users may obtain the IGRF-12 model coefficients in electronic form, software for evaluating the model, and a "health warning" concerning the use of IGRF-12, online at http://www.ngdc.noaa.gov/IAGA/vmod/igrf.html.

It should be appreciated that the update of the IGRF is an enterprise of general scientific interest. It is the occasion to strengthen the cooperation between scientists involved in modeling the magnetic field, the institutions archiving and disseminating the ground magnetic field data, the national and the various space agencies, and sometimes industry. This close link between science and industry is well illustrated by the article of Léger et al. (2015) who discuss and demonstrate the in-flight performances of a new type of scalar magnetometer that is onboard the three European *Swarm* satellites. The magnetometers can also be run in a vector mode and generate measurements that were exclusively and successfully used by Vigneron et al. (2015) to derive their candidate model to IGRF-12 for epoch 2015.0. The malfunction of one of the absolute scalar magnetometers on one of the three Swarm satellites has deprived the scientific community of some of these innovative measurements but prompted a probabilistic analysis of failure to help guide decisions regarding the *Swarm*'s satellite orbit deployment (Jackson, 2015). For scientists, the IGRF update is a general opportunity to assess the scope of geomagnetism as a discipline and to analyze the scientific and societal needs for such an operational model. The IGRF task force, through the call for IGRF candidate models, gives only technical and minimum specifications but no clear recommendation about what source field IGRF that should represent. Should IGRF represent the Earth's magnetic core field only? Should all large scale internal fields, including fields induced by the external field in the Earth's mantle, be included? These questions again lead to debate amongst the IGRF task force members and other scientists interested in IGRF. However, offering flexibility to modelers arguably stimulates innovation, guarantees that some candidate models are independent, and aids in making the IGRF model valid on average for a wide range of disparate applications. This latter important aspect can be illustrated with a short investigation on how IGRF models are used.

The IGRF models are used in scientific and societal applications for mapping, drilling or navigation, and orientation (e.g., Meyers and Davis, 1990). During the past decade, this traditional landscape has been supplemented by the emergence of new applications. A systematic investigation about the use of IGRF through 50 years is difficult, but a glimpse into its use in scientific studies over the last decade can be obtained by searching the Web of Science™. Between 2005 and August 2015, the three main papers about the tenth generation of IGRF (Macmillan et al. 2005 and Maus et al. 2005a; Maus et al. 2005b) were cited about 246 times in peer reviewed publications (in the Web of Sience™ Core Collection). The following IGRF-11 generation (Finlay et al. 2010) received 315 citations between 2010 and August 2015. The citing papers can be classified in five arbitrary science categories. The first category, *Geophysics and Geochemistry*, contains papers dealing with the internal and/or deep Earth. These include research areas such as physics of the Earth's core, mantle, and crust. The second category, *Aeronomy/Astronomy*, pulls together papers on external ionospheric and magnetospheric fields and their interaction with the solar wind on a global spatial scale. The third category, *Space Weather/Ionosphere*, contains a collection of articles dealing mostly with transient magnetic phenomena occurring in the upper atmosphere. These three categories include almost all academic works related to the study of the Earth system. The fourth category, *Engineering/Remote sensing*, includes paper about instrumentation, telecommunication, and space technologies. The last category, *Life Siences/Medecine*, gathers a wide variety of topics investigating the possible links between (geo) magnetic field conditions and life. Some categories such as the second and third contain closely related field of interests which are not easy to separate objectively. Some overlap between the categories is not ruled out, and the percentage distribution of each research area provides only a crude picture of the scientific use of IGRF models through the last decade.

Figure 1 shows that between 2005 and 2015 (left panel), the IGRF-10 was mostly used for "traditional" scientific purposes such as internal and external field geophysics. These activities, comprising navigation, surveying, and prospecting, represent almost 80 % of the scientific uses of IGRF-10; IGRF-10 was apparently used only occasionally in Engineering (6 %) and Life Sciences (3 %). The large percentage of use for fundamental geophysical research is consistent with the outcome of the study of Meyers and Davis (1990) relying on a survey conducted directly with 144 users from 1 October 1987 through 6 June 1989. It can also be verified using the Web of Science™ that the three first categories absorb more than 80 % of the citations from the third to the tenth generation of IGRF (note that the Web of Science™ is perhaps less reliable in counting citations at older epochs). However, from 2010 onwards, users citing the updated IGRF-11 used the series of models also for other purposes. The proportion of papers citing IGRF-11 for internal and external geomagnetic field purposes decreased notably (down to 70 %; Fig. 1, right panel) while the proportion of research involving the science area *Engineering/Remote sensing* (24 %) rose. This increasing number of IGRF citations in this category in recent years is due to primarily researches carried out in aerospace engineering that seek to address communication issues from space and challenges in positioning miniaturized satellites. The statistics accessible from Web of Science™ provide only a limited insight concerning the typical IGRF user. Most users do not inform the IAGA V-MOD working group about their intention to use IGRF so their number is unknown. IGRF model coefficients and computation codes are embedded in a number of commercial Software packages (Matlab®, Geosoft, for instance) dedicated to engineering and operational activities. They are also often used for educational and personal purposes. Most GPS receivers include the IGRF or the World Magnetic Model (https://www.ngdc.noaa.gov/geomag/WMM/DoDWMM.shtml) in their firmware for converting true courses and bearings into magnetic ones. The analytics set up on the IGRF web page (http://www.ngdc.noaa.gov/IAGA/vmod/igrf.html) in May 2015 shows that 7963 unique users navigated on the IGRF web site from 28 May 2015 to 13 August 2015 (C. Manoj, National Centers for Environmental Information, personal communication). If the exact number of visitors who downloaded the coefficients file is unknown, we learn that 10 % of them cared to visit the IGRF "Health warning" page and showed enough interest to stay there long enough to read the recommendations. A similar log monitoring carried out by the British Geological Survey (S. Macmillan, S. Reay and C. Beggan, personal communication) indicates that the IGRF-11 online calculator received about 580 requests per month from January 2010 to July 2015 and that 7082 requests from January 2015 are associated with entries of positional data and date using IGRF-12. All these requests were done by humans and not visiting spider or robot programs.

This wide community of users has a range of different needs that justifies some flexibility in the IGRF specifications. The increasing interest in IGRF for space applications may, for example, lead IAGA to consider in the future the introduction of models for magnetic sources internal to satellite orbits, including the magnetic field generated by currents flowing in the ionosphere or also quasi-static magnetospheric field contributions. In this

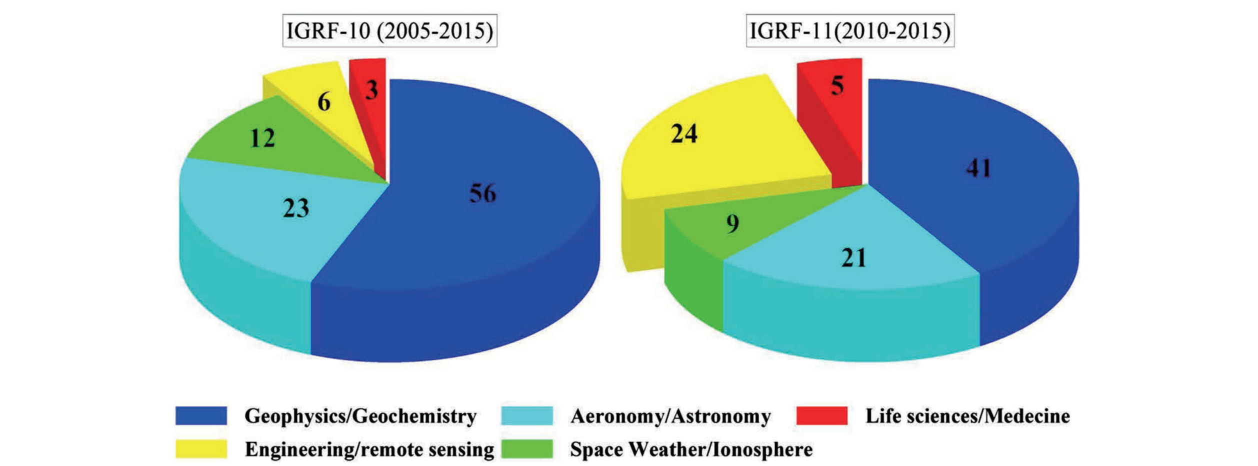

Fig. 1 Percentage by category of science papers citing the IGRF-10 between 2005 and 2015 (*left*) and citing the IGRF-11 paper between 2010 and 2015 (*right*)

regard, the IGRF task force, whose role is to discuss and define the IGRF specifications, will seek to guarantee that IGRF activities will stay at the forefront of geomagnetism and deliver a product that best serves science and society.

The IGRF-12 results from major collaborative effort, and we wish in particular to thank the authors of the papers presented here, the many referees who gave their time and shared their expertise, and the EPS Chief Editor Yasuo Ogawa for his support with this special issue.

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FRONTIER LETTER **Open Access**

In-flight performance of the Absolute Scalar Magnetometer vector mode on board the Swarm satellites

Jean-Michel Léger, Thomas Jager*, François Bertrand, Gauthier Hulot, Laura Brocco, Pierre Vigneron, Xavier Lalanne, Arnaud Chulliat and Isabelle Fratter

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Abstract

The role of the Absolute Scalar Magnetometer (ASM) in the European Space Agency (ESA) Swarm mission is to deliver absolute measurements of the magnetic field's strength for science investigations and in-flight calibration of the Vector Field Magnetometer (VFM). However, the ASM instrument can also simultaneously deliver vector measurements with no impact on the magnetometer's scalar performance, using a so-called vector mode. This vector mode has been continuously operated since the beginning of the mission, except for short periods of time during commissioning. Since both scalar and vector measurements are perfectly synchronous and spatially coherent, a direct assessment of the ASM vector performance can then be carried out at instrument level without need to correct for the various magnetic perturbations generated by the satellites. After a brief description of the instrument's operating principles, a thorough analysis of the instrument's behavior is presented, as well as a characterization of its environment in flight, using an alternative high sampling rate (burst) scalar mode that could be run a few days during commissioning. The ASM vector calibration process is next detailed, with some emphasis on its sensitivity to operational conditions. Finally, the evolution of the instrument's performance during the first year of the mission is presented and discussed in view of the mission's performance requirements for vector measurements.

Keywords: Swarm; He4 magnetometer; Scalar absolute magnetometer; Vector magnetometer; Vector calibration

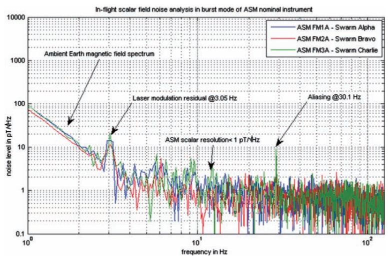

Figure 1

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FULL PAPER **Open Access**

NOAA/NGDC candidate models for the 12th generation International Geomagnetic Reference Field

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Abstract

The International Geomagnetic Reference Field (IGRF) is a model of the geomagnetic main field and its secular variation, produced every 5 years from candidate models proposed by a number of international research institutions. For this 12th generation IGRF, three candidate models were solicited: a main field model for the 2010.0 epoch, a main field model for the 2015.0 epoch, and the predicted secular variation for the five-year period 2015 to 2020. The National Geophysical Data Center (NGDC), part of the National Oceanic and Atmospheric Administration (NOAA), has produced three candidate models for consideration in IGRF-12. The 2010 main field candidate was produced from Challenging Minisatellite Payload (CHAMP) satellite data, while the 2015 main field and secular variation candidates were produced from Swarm and Ørsted satellite data. Careful data selection was performed to minimize the influence of magnetospheric and ionospheric fields. The secular variation predictions of our parent models, from which the candidate models were derived, have been validated against independent ground observatory data.

Keywords: Geomagnetic field; Magnetic field modeling; IGRF; Swarm

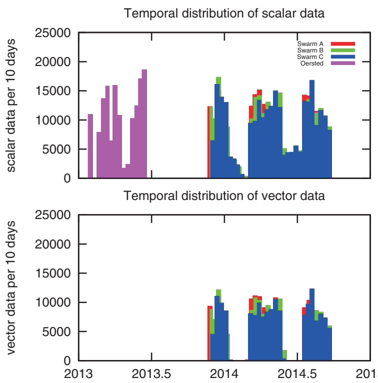

Figure 1

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FULL PAPER **Open Access**

The BGS magnetic field candidate models for the 12th generation IGRF

Brian Hamilton*, Victoria A Ridley, Ciarán D Beggan and Susan Macmillan

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Abstract

We describe the candidate models submitted by the British Geological Survey for the 12th generation International Geomagnetic Reference Field. These models are extracted from a spherical harmonic 'parent model' derived from vector and scalar magnetic field data from satellite and observatory sources. These data cover the period 2009.0 to 2014.7 and include measurements from the recently launched European Space Agency (ESA) Swarm satellite constellation. The parent model's internal field time dependence for degrees 1 to 13 is represented by order 6 B-splines with knots at yearly intervals. The parent model's degree 1 external field time dependence is described by periodic functions for the annual and semi-annual signals and by dependence on the 20-min Vector Magnetic Disturbance index. Signals induced by these external fields are also parameterized. Satellite data are weighted by spatial density and by two different noise estimators: (a) by standard deviation along segments of the satellite track and (b) a larger-scale noise estimator defined in terms of a measure of vector activity at the geographically closest magnetic observatories to the sample point. Forecasting of the magnetic field secular variation beyond the span of data is by advection of the main field using core surface flows.

Keywords: IGRF; Geomagnetic field; Geomagnetic secular variation; Swarm

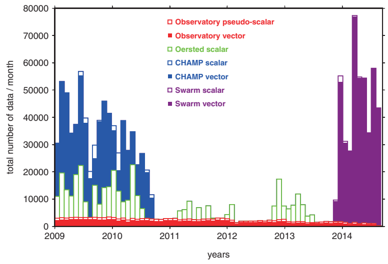

Figure 1

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FULL PAPER **Open Access**

Stochastic forecasting of the geomagnetic field from the COV-OBS.x1 geomagnetic field model, and candidate models for IGRF-12

Nicolas Gillet*, Olivier Barrois and Christopher C Finlay

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Abstract

We present the geomagnetic field model COV-OBS.x1, covering 1840 to 2020, from which have been derived candidate models for the IGRF-12. Towards the most recent epochs, it is primarily constrained by first differences of observatory annual means and measurements from the Oersted, Champ, and Swarm satellite missions. Stochastic information derived from the temporal spectra of geomagnetic series is used to construct the *a priori* model covariance matrix that complements the constraint brought by the data. This approach makes it possible the use of *a posteriori* model errors, for instance, to measure the 'observations' uncertainties in data assimilation schemes for the study of the outer core dynamics.

We also present and illustrate a stochastic algorithm designed to forecast the geomagnetic field. The radial field at the outer core surface is advected by core motions governed by an auto-regressive process of order 1. This particular choice is motivated by the slope observed for the power spectral density of geomagnetic series. Accounting for time-correlated model errors (subgrid processes associated with the unresolved magnetic field) is made possible thanks to the use of an augmented state ensemble Kalman filter algorithm. We show that the envelope of forecasts includes the observed secular variation of the geomagnetic field over 5-year intervals, even in the case of rapid changes. In a purpose of testing hypotheses about the core dynamics, this prototype method could be implemented to build the 'state zero' of the ability to forecast the geomagnetic field, by measuring what can be predicted when no deterministic physics is incorporated into the dynamical model.

Keywords: Geomagnetic field; Secular variation; Stochastic equations; Ensemble Kalman filter

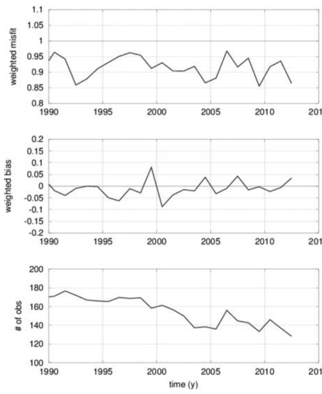

Figure 1

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FULL PAPER **Open Access**

A candidate secular variation model for IGRF-12 based on Swarm data and inverse geodynamo modelling

Alexandre Fournier*, Julien Aubert and Erwan Thébault

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Abstract
In the context of the 12th release of the international geomagnetic reference field (IGRF), we present the methodology we followed to design a candidate secular variation model for years 2015–2020. An initial geomagnetic field model centered around 2014.3 is first constructed, based on Swarm magnetic measurements, for both the main field and its instantaneous secular variation. This initial model is next fed to an inverse geodynamo modelling framework in order to specify, for epoch 2014.3, the initial condition for the integration of a three-dimensional numerical dynamo model. The initialization phase combines the information contained in the initial model with that coming from the numerical dynamo model, in the form of three-dimensional multivariate statistics built from a numerical dynamo run unconstrained by data.
We study the performance of this novel approach over two recent 5-year long intervals, 2005–2010 and 2009–2014. For a forecast horizon of 5 years, shorter than the large-scale secular acceleration time scale (~10 years), we find that it is safer to neglect the flow acceleration and to assume that the flow determined by the initialization is steady. This steady flow is used to advance the three-dimensional induction equation forward in time, with the benefit of estimating the effects of magnetic diffusion. The result of this deterministic integration between 2015.0 and 2020.0 yields our candidate average secular variation model for that time frame, which is thus centered on 2017.5.

Keywords: Magnetic field; Satellite magnetics; Dynamo: theories and simulations; Inverse theory

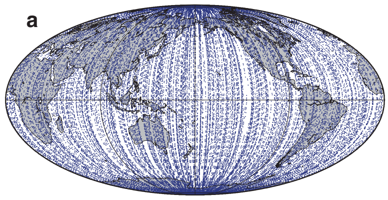

Figure 1

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FULL PAPER **Open Access**

Parent magnetic field models for the IGRF-12 GFZ-candidates

Vincent Lesur*, Martin Rother, Ingo Wardinski, Reyko Schachtschneider, Mohamed Hamoudi and Aude Chambodut

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Abstract
We propose candidate models for IGRF-12. These models were derived from parent models built from 10 months of Swarm satellite data and 1.5 years of magnetic observatory data. Using the same parameterisation, a magnetic field model was built from a slightly extended satellite data set. As a result of discrepancies between magnetic field intensity measured by the absolute scalar instrument and that calculated from the vector instrument, we re-calibrated the satellite data. For the calibration, we assumed that the discrepancies resulted from a small perturbing magnetic field carried by the satellite, with a strength and orientation dependent on the Sun's position relative to the satellite. Scalar and vector data were reconciled using only a limited number of calibration parameters. The data selection process, followed by the joint modelling of the magnetic field and Euler angles, leads to accurate models of the main field and its secular variation around 2014.0. The obtained secular variation model is compared with models based on CHAMP satellite data. The comparison suggests that pulses of magnetic field acceleration that were observed on short time scales average-out over a decade.

Keywords: IGRF-12; Swarm satellite mission; Geomagnetic field models

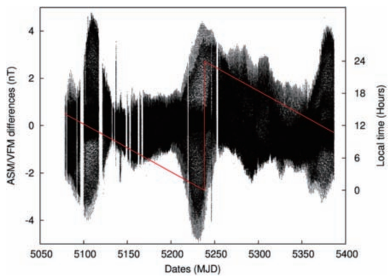

Figure 1

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FULL PAPER **Open Access**

A 2015 International Geomagnetic Reference Field (IGRF) candidate model based on *Swarm's* experimental absolute magnetometer vector mode data

Pierre Vigneron, Gauthier Hulot*, Nils Olsen, Jean-Michel Léger, Thomas Jager, Laura Brocco, Olivier Sirol, Pierdavide Coïsson, Xavier Lalanne, Arnaud Chulliat, François Bertrand, Axel Boness and Isabelle Fratter

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Abstract

Each of the three satellites of the European Space Agency *Swarm* mission carries an absolute scalar magnetometer (ASM) that provides the nominal 1-Hz scalar data of the mission for both science and calibration purposes. These ASM instruments, however, also deliver autonomous 1-Hz experimental vector data. Here, we report on how ASM-only scalar and vector data from the Alpha and Bravo satellites between November 29, 2013 (a week after launch) and September 25, 2014 (for on-time delivery of the model on October 1, 2014) could be used to build a very valuable candidate model for the 2015.0 International Geomagnetic Reference Field (IGRF). A parent model was first computed, describing the geomagnetic field of internal origin up to degree and order 40 in a spherical harmonic representation and including a constant secular variation up to degree and order 8. This model was next simply forwarded to epoch 2015.0 and truncated at degree and order 13. The resulting ASM-only 2015.0 IGRF candidate model is compared to analogous models derived from the mission's nominal data and to the now-published final 2015.0 IGRF model. Differences among models mainly highlight uncertainties enhanced by the limited geographical distribution of the selected data set (essentially due to a lack of availability of data at high northern latitude satisfying nighttime conditions at the end of the time period considered). These appear to be comparable to differences classically observed among IGRF candidate models. These positive results led the ASM-only 2015.0 IGRF candidate model to contribute to the construction of the final 2015.0 IGRF model.

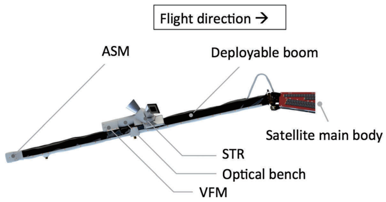

Figure 1

Keywords: Swarm; IGRF; Absolute vector magnetometer

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FULL PAPER **Open Access**

POGO satellite orbit corrections: an opportunity to improve the quality of the geomagnetic field measurements?

Reto Stockmann*, Freddy Christiansen, Nils Olsen and Andrew Jackson*

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Abstract

We present an attempt to improve the quality of the geomagnetic field measurements from the Polar Orbiting Geophysical Observatory (POGO) satellite missions in the late 1960s. Inaccurate satellite positions are believed to be a major source of errors for using the magnetic observations for field modelling. To improve the data, we use an iterative approach consisting of two main parts: one is a main field modelling process to obtain the radial field gradient to perturb the orbits and the other is the state-of-the-art GPS orbit modelling software BERNESE to calculate new physical orbits. We report results based on a single-day approach showing a clear increase of the data quality. That single-day approach leads, however, to undesirable orbital jumps at midnight. Furthermore, we report results obtained for a much larger data set comprising almost all of the data from the three missions. With this approach, we eliminate the orbit discontinuities at midnight but only tiny quality improvements could be achieved for geomagnetically quiet data. We believe that improvements to the data are probably still possible, but it would require the original tracking observations to be found.

Keywords: Inverse theory; Satellite magnetics; Satellite orbits

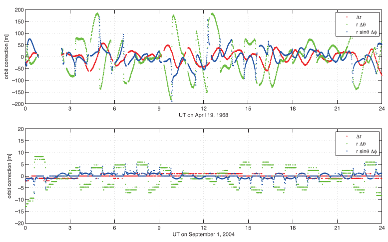
Figure 1

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FULL PAPER Open Access

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

Christopher C Finlay*, Nils Olsen and Lars Tøffner-Clausen

Earth, Planets and Space 2015, **67**:114 doi:10.1186/s40623-015-0274-3
Received: 10 February 2015, Accepted: 15 June 2015, Published: 22 July 2015

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*

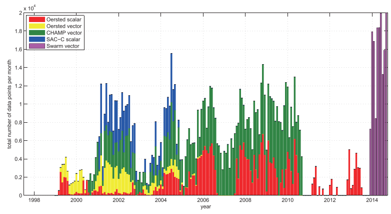

Figure 1

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LETTER Open Access

International Geomagnetic Reference Field: the 12th generation

Erwan Thébault*, Christopher C Finlay, Ciarán D Beggan, Patrick Alken, Julien Aubert, Olivier Barrois, Francois Bertrand, Tatiana Bondar, Axel Boness, Laura Brocco, Elisabeth Canet, Aude Chambodut, Arnaud Chulliat, Pierdavide Coïsson, François Civet, Aimin Du, Alexandre Fournier, Isabelle Fratter, Nicolas Gillet, Brian Hamilton, Mohamed Hamoudi, Gauthier Hulot, Thomas Jager, Monika Korte, Weijia Kuang, Xavier Lalanne, Benoit Langlais, Jean-Michel Léger, Vincent Lesur, Frank J Lowes, Susan Macmillan, Mioara Mandea, Chandrasekharan Manoj, Stefan Maus, Nils Olsen, Valeriy Petrov, Victoria Ridley, Martin Rother, Terence J Sabaka, Diana Saturnino, Reyko Schachtschneider, Olivier Sirol, Andrew Tangborn, Alan Thomson, Lars Tøffner-Clausen, Pierre Vigneron, Ingo Wardinski and Tatiana Zvereva

Earth, Planets and Space 2015, **67**:79 doi:10.1186/s40623-015-0228-9
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Abstract

The 12th generation of the International Geomagnetic Reference Field (IGRF) was adopted in December 2014 by the Working Group V-MOD appointed by the International Association of Geomagnetism and Aeronomy (IAGA). It updates the previous IGRF generation with a definitive main field model for epoch 2010.0, a main field model for epoch 2015.0, and a linear annual predictive secular variation model for 2015.0-2020.0. Here, we present the equations defining the IGRF model, provide the spherical harmonic coefficients, and provide maps of the magnetic declination, inclination, and total intensity for epoch 2015.0 and their predicted rates of change for 2015.0-2020.0. We also update the magnetic pole positions and discuss briefly the latest changes and possible future trends of the Earth's magnetic field.

Keywords: Geomagnetism; Field modeling; IGRF

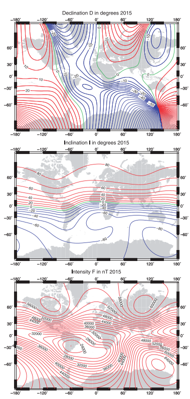

Figure 1

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LETTER **Open Access**

Main field and secular variation candidate models for the 12th IGRF generation after 10 months of Swarm measurements

Diana Saturnino*, Benoit Langlais, François Civet, Erwan Thébault and Mioara Mandea

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Abstract

We describe the main field and secular variation candidate models for the 12th generation of the International Geomagnetic Reference Field model. These two models are derived from the same parent model, in which the main field is extrapolated to epoch 2015.0 using its associated secular variation. The parent model is exclusively based on measurements acquired by the European Space Agency Swarm mission between its launch on 11/22/2013 and 09/18/2014. It is computed up to spherical harmonic degree and order 25 for the main field, 13 for the secular variation, and 2 for the external field. A selection on local time rather than on true illumination of the spacecraft was chosen in order to keep more measurements. Data selection based on geomagnetic indices was used to minimize the external field contributions. Measurements were screened and outliers were carefully removed. The model uses magnetic field intensity measurements at all latitudes and magnetic field vector measurements equatorward of 50° absolute quasi-dipole magnetic latitude. A second model using only the vertical component of the measured magnetic field and the total intensity was computed. This companion model offers a slightly better fit to the measurements. These two models are compared and discussed.We discuss in particular the quality of the model which does not use the full vector measurements and underline that this approach may be used when only partial directional information is known. The candidate models and their associated companion models are retrospectively compared to the adopted IGRF which allows us to criticize our own choices.

Keywords: Magnetic field; Main field; Secular variation; Modeling; IGRF; Time extrapolation

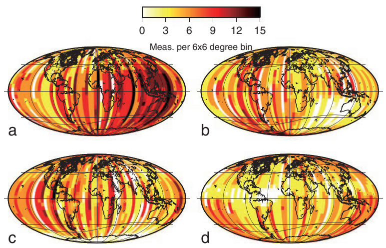

Figure 1

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LETTER **Open Access**

A probabilistic analysis of the implications of instrument failures on ESA's Swarm mission for its individual satellite orbit deployments

Andrew Jackson

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Abstract

On launch, one of Swarm's absolute scalar magnetometers (ASMs) failed to function, leaving an asymmetrical arrangement of redundant spares on different spacecrafts. A decision was required concerning the deployment of individual satellites into the low-orbit pair or the higher "lonely" orbit. I analyse the probabilities for successful operation of two of the science components of the Swarm mission in terms of a classical probabilistic failure analysis, with a view to concluding a favourable assignment for the satellite with the single working ASM. I concentrate on the following two science aspects: the east-west gradiometer aspect of the lower pair of satellites and the constellation aspect, which requires a working ASM in each of the two orbital planes. I use the so-called "expert solicitation" probabilities for instrument failure solicited from Mission Advisory Group (MAG) members. My conclusion from the analysis is that it is better to have redundancy of ASMs in the lonely satellite orbit. Although the opposite scenario, having redundancy (and thus four ASMs) in the lower orbit, increases the chance of a working gradiometer late in the mission; it does so at the expense of a likely constellation. Although the results are presented based on actual MAG members' probabilities, the results are rather generic, excepting the case when the probability of individual ASM failure is very small; in this case, any arrangement will ensure a successful mission since there is essentially no failure expected at all. Since the very design of the lower pair is to enable common mode rejection of external signals, it is likely that its work can be successfully achieved during the first 5 years of the mission.

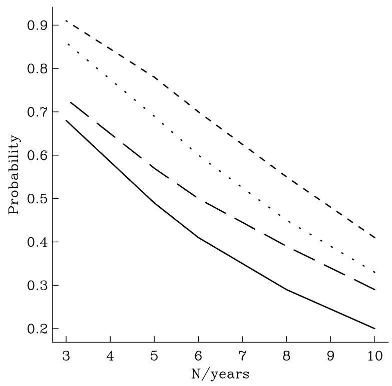

Figure 1

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TECHNICAL REPORT **Open Access**

Evaluation of candidate geomagnetic field models for IGRF-12

Erwan Thébault*, Christopher C. Finlay, Patrick Alken, Ciaran D. Beggan, Elisabeth Canet, Arnaud Chulliat, Benoit Langlais, Vincent Lesur, Frank J. Lowes, Chandrasekharan Manoj, Martin Rother and Reyko Schachtschneider

Earth, Planets and Space 2015, **67**:112 doi:10.1186/s40623-015-0273-4

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Abstract

Background: The 12th revision of the International Geomagnetic Reference Field (IGRF) was issued in December 2014 by the International Association of Geomagnetism and Aeronomy (IAGA) Division V Working Group V-MOD (http://www.ngdc.noaa.gov/IAGA/vmod/igrf.html). This revision comprises new spherical harmonic main field models for epochs 2010.0 (DGRF-2010) and 2015.0 (IGRF-2015) and predictive linear secular variation for the interval 2015.0-2020.0 (SV-2010-2015).

Findings: The models were derived from weighted averages of candidate models submitted by ten international teams. Teams were led by the British Geological Survey (UK), DTU Space (Denmark), ISTerre (France), IZMIRAN (Russia), NOAA/NGDC (USA), GFZ Potsdam (Germany), NASA/GSFC (USA), IPGP (France), LPG Nantes (France), and ETH Zurich (Switzerland). Each candidate model was carefully evaluated and compared to all other models and a mean model using well-defined statistical criteria in the spectral domain and maps in the physical space. These analyses were made to pinpoint both troublesome coefficients and the geographical regions where the candidate models most significantly differ. Some models showed clear deviation from other candidate models. However, a majority of the task force members appointed by IAGA thought that the differences were not sufficient to exclude models that were well documented and based on different techniques.

Conclusions: The task force thus voted for and applied an iterative robust estimation scheme in space. In this paper, we report on the evaluations of the candidate models and provide details of the algorithm that was used to derive the IGRF-12 product.

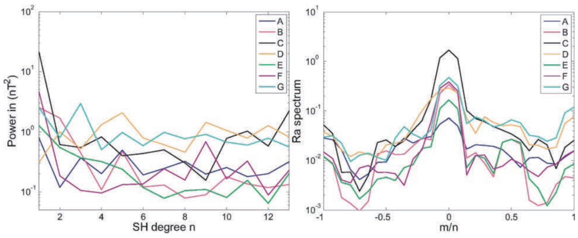

Figure 1

Keywords: Geomagnetism; Field modeling; IGRF

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Correspondence

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