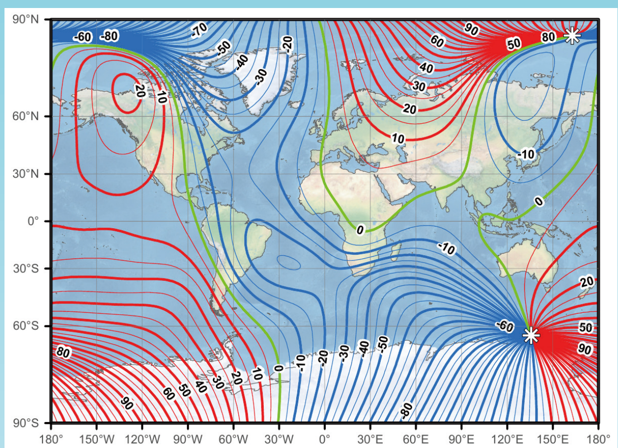
Earth, Planets and Space

International Geomagnetic Reference Field - The Thirteenth Generation



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Alken *et al. Earth, Planets and Space (2022) 74:11*
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PREFACE **Open Access**

Special issue "International Geomagnetic Reference Field: the thirteenth generation"

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The large-scale time-varying portion of Earth's internal magnetic field originates from a dynamo process inside the outer core. This geodynamo drives changes in Earth's magnetic field on timescales ranging from less than 1 year to hundreds of millions of years. Monitoring the large-scale internal geomagnetic field and its temporal variations is fundamental to improving our understanding of our planet's interior dynamics, as well as maintaining and developing technology designed to utilize magnetic field observations for the benefit of society.

The International Geomagnetic Reference Field (IGRF) is a mathematical representation of the large-scale, time-varying, internal part of Earth's magnetic field. The IGRF consists of a set of model coefficients which can be input into a mathematical equation to produce the three vector components of the geomagnetic field from the surface of the core mantle boundary (about 2900 km below the Earth's surface), to low-Earth orbiting satellite altitudes. The 13th generation IGRF (IGRF-13), which is the subject of this special issue, provides model coefficients from 1900 to 2025, allowing a description of the geomagnetic field over the past one and one quarter centuries. The IGRF is a truly international collaboration, by which multiple teams of magnetic field experts submit candidate model coefficients to improve past model predictions, as well as make forecasts for the next 5 year period.

The 13th generation IGRF received a record number of candidate model submissions from a total of 15 international teams. Eleven candidate models were received to update the geomagnetic field description at the epoch 2015.0. Twelve candidate models were received for the epoch 2020.0. And finally fourteen candidate models were received to forecast the field evolution over the period 2020 to 2025. A task force was assembled to evaluate each candidate model and combine all candidates into a final set of model coefficients for IGRF-13. The findings of this task force are documented in Alken et al. (2021b). A summary of the final IGRF-13 model is presented in Alken et al. (2021c). Each team who participated in IGRF-13 prepared manuscripts detailing their work, which are collected into this special issue. Below, we provide a brief description of the methods used for building their candidate models.

Brown et al. (2021) describes three candidate models submitted by the British Geological Survey based on data from the European Swarm satellite mission and ground observatories. They discuss their main field candidates for 2015.0 and 2020.0 as well as a secular variation forecast (2020 to 2025) based on advection of the main field using steady core surface flow modeling. They additionally provide a retrospective analysis of the IGRF-12 secular variation forecasts.

Yang et al. (2021) present the only IGRF-13 candidate model which did not utilize data from the Swarm mission. Instead, they used measurements from the China Seismo-Electromagnetic Satellite (CSES) to build a main field candidate for epoch 2020.0 and performed a validation analysis comparing their model with the other candidate models for epoch 2020.0. The lead institute for this candidate is the China Earthquake Administration.

Pavón-Carrasco et al. (2020) present main field candidate models for epochs 2015.0 and 2020.0, as well as a secular variation forecast for 2020 to 2025 submitted by the Universidad Complutense de Madrid. They developed a bootstrapping method to build models from

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Swarm and ground observatory data which allowed them to provide uncertainties on their candidate model coefficients.

Alken et al. (2021a) detail the candidate models submitted by NOAA/NCEI and the University of Colorado. They present main field candidates for epochs 2015.0 and 2020.0, as well as a secular variation forecast for 2020 to 2025. Swarm satellite measurements were their primary data source, supplemented by ground observatory measurements for validation. They additionally provide a retrospective assessment of their previous IGRF-12 candidate model.

Finlay et al. (2020) presents the CHAOS-7 geomagnetic field model, which served as the parent model for the Danish Technical University candidates to IGRF-13. They built a model spanning more than two decades using data from Ørsted, CHAMP, SAC-C, Cryosat-2, Swarm, and the ground observatory network. In addition to discussing their IGRF-13 candidates, they analyze the recent behavior of the South Atlantic Anomaly.

Rother et al. (2021) presents the Mag.num geomagnetic core field model developed at GeoForschungsZentrum (GFZ) Potsdam, which served as the parent model for that institute's IGRF-13 candidates. This model used Swarm and ground observatory data to construct candidates for the main field at 2015.0 and 2020.0 as well as a secular variation forecast for 2020 to 2025. They additionally analyze recent trends of the South Atlantic Anomaly.

The Institut de Physique du Globe de Paris (IPGP) provided three candidate models to IGRF-13 which are detailed in three separate papers in this special issue. Vigneron et al. (2021) presents a main field candidate for epoch 2015.0 using the experimental vector mode on Swarm's absolute scalar magnetometer (ASM-V). Ropp et al. (2020) presents a novel approach to core field estimation by combining a sequential modeling approach, a Kalman filter, and a correlation-based modeling step. Their method was used for the IPGP main field candidate for epoch 2020.0. Fournier et al. (2021a) presents the IPGP secular variation candidate model to IGRF-13 based on integrating an ensemble of 100 geodynamo models between epochs 2019.0 and 2025.0, with each ensemble member differing only in initial conditions.

Huder et al. (2020) detail the candidate models to IGRF-13 submitted by the Institut des Sciences de la Terre (ISTerre). They construct a model named COV-OBS.x2 covering the time period 1840 to 2020, integrating ground observatory data, satellite data, and older surveys. This team submitted main field candidates for epochs 2015.0 and 2020.0, as well as a secular variation forecast for 2020 to 2025.

Petrov and Bondar (2021) present the IGRF-13 candidates submitted by the Pushkov Institute of Terrestrial Magnetism (IZMIRAN), which included main field candidates for epoch 2015.0 and 2020.0, as well as a secular variation forecast for 2020 to 2025. Their approach was to bin Swarm measurements into discrete cells covering Earth's surface and applying spherical harmonic analysis to the resulting grid.

Minami et al. (2020) present an IGRF-13 candidate secular variation forecast for 2020 to 2025 developed by several research groups in Japan. Their methodology applied a data assimilation scheme to a magnetohydrodynamic (MHD) dynamo simulation code. Their data assimilation method incorporated measurements from CHAMP, Swarm, and the ground observatory network.

Metman et al. (2020) detail a secular variation forecast candidate to IGRF-13 developed at the University of Leeds. They use secular variation estimates provided by the CHAOS-6 model to fit a steady core flow model, followed by fitting the residual to a magnetic diffusion model in order to provide a forecast over the 2020 to 2025 time period.

Sanchez et al. (2020) present the Max Planck Institute for Solar System Research secular variation candidate for IGRF-13. They use a sequential ensemble data assimilation method, with the ensembles consisting of parallel 3D dynamo simulations. The input data to the assimilation comes from the COV-OBS.x1 and Kalmag models.

The NASA candidates to IGRF-13 are detailed in two publications in this special issue. Sabaka et al. (2020) present the latest development in the Comprehensive Model (CM) series, culminating in a model called CM6 which includes Ørsted, SAC-C, CHAMP and Swarm satellites, and ground observations. CM6 models not only the core field, but also contributions from the lithosphere, ionosphere, magnetosphere, and oceanic tides. CM6 was used to generate main field candidates for epochs 2015.0 and 2020.0. Tangborn et al. (2021) present a secular variation forecast for 2020 to 2025 combining a geodynamo model with an ensemble Kalman filter. Various geomagnetic field models are used as inputs to the data assimilation scheme.

Baerenzung et al. (2020) detail the University of Potsdam candidate models for IGRF-13. They present a model named Kalmag, which assimilates CHAMP and Swarm data using a Kalman filter scheme, and has a validity period spanning two decades. This team submitted main field candidates for epochs 2015.0 and 2020.0, as well as a secular variation forecast for 2020 to 2025.

Wardinski et al. (2020) present the Université de Strasbourg's candidate model submissions to IGRF-13. They combine satellite and ground measurements to build a continuous model of the main field and its secular variation from 1957 to 2020. This approach was used to derive main field candidates for 2015.0 and 2020.0, as well as a secular variation forecast for 2020 to 2025 based on a multi-variate singular spectrum analysis of the secular variation recorded over the past six decades.

Finally, Fournier et al. (2021b) contributed a Frontier letter to this special issue, on the topic of secular variation forecasting. Recent satellite observations have revealed significant short time-scale variations in the geomagnetic field which are difficult to predict by routinely used methods to extrapolate current measurements several years into the future. These authors analyze 35 years of past IGRF secular variation forecasts and find that the quality of 5-year forecasts deteriorates significantly during times of rapid geomagnetic field changes. They review the current state-of-the-art methods in physics-based forecasting of secular variation, discuss lessons learned over the past several decades, and comment on possible future directions.

The task force thanks all the participants for providing their time, resources and expertise to create the main field models and forecasts for this generation of the IGRF. We also thank the many data providers for the freely-available scientific magnetic data, without which it would not be possible to produce such high quality models.

Authors' contributions
PA is chair of the IAGA DIV V-MOD (2019–2023) and initiated, coordinated and organised the call and delivery of the 13th generation of the IGRF. ET is former chair (2015–2019). CB is present co-chair (2019–2023). All authors have read and approved the manuscript.

Availability of data and materials
Not applicable.

Declarations

Competing interests
The authors declare that they have no competing interests.

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Publisher's Note

FRONTIER LETTER Open Access

Physics-based secular variation candidate models for the IGRF

Alexandre Fournier*, Julien Aubert, Vincent Lesur and Erwan Thébault

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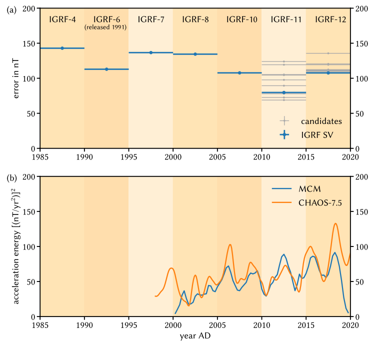
Abstract

Each International Geomagnetic Reference Field (IGRF) model released under the auspices of the International Association of Geomagnetism and Aeronomy comprises a secular variation component that describes the evolution of the main magnetic field anticipated for the 5 years to come. Every Gauss coefficient, up to spherical harmonic degree and order 8, is assumed to undergo its own independent linear evolution. With a mathematical model of the core magnetic field and its time rate of change constructed from geomagnetic observations at hand, a standard prediction of the secular variation (SV) consists of taking the time rate of change of each Gauss coefficient at the final time of analysis as the predicted rate of change. The last three generations of the IGRF have additionally witnessed a growing number of candidate SV models relying upon physics-based forecasts. This surge is motivated by satellite data that now span more than two decades and by the concurrent progress in the numerical modelling of Earth's core dynamics. Satellite data reveal rapid (interannual) geomagnetic features whose imprint can be detrimental to the quality of the IGRF prediction. This calls for forecasting frameworks able to incorporate at least part of the processes responsible for short-term geomagnetic variations. In this letter, we perform a retrospective analysis of the performance of past IGRF SV models and candidates over the past 35 years; we emphasize that over the satellite era, the quality of the 5-year forecasts worsens at times of rapid geomagnetic changes. After the definition of the time scales that are relevant for the IGRF prediction exercise, we cover the strategies followed by past physics-based candidates, which we categorize into a "core–surface flow" family and a "dynamo" family, noting that both strategies resort to "input" models of the main field and its secular variation constructed from observations. We next review practical lessons learned from our previous attempts. Finally, we discuss possible improvements on the current state of affairs in two directions: the feasibility of incorporating rapid physical processes into the analysis on the one hand, and the accuracy and quantification of the uncertainty impacting input models on the other hand.

Keywords: Earth's magnetic field, Geomagnetic secular variation, Geomagnetic secular acceleration, Dynamo: theory and simulation, Convection, Magnetohydrodynamic waves, Inverse theory



Graphical abstract

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FULL PAPER Open Access

CM6: a comprehensive geomagnetic field model derived from both CHAMP and Swarm satellite observations

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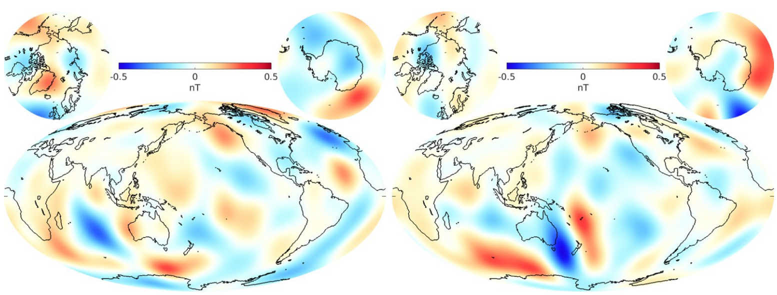
Abstract

From the launch of the Ørsted satellite in 1999, through the CHAMP mission from 2000 to 2010, and now with the Swarm constellation mission starting in 2013, satellite magnetometry has provided excellent monitoring of the near-Earth magnetic field regime. The advanced Comprehensive Inversion scheme has been applied to data before Swarm and to the Swarm data itself, but now for the first time to all the satellite data in this new era, culminating in the CM6 model. The highlights of this model include not only a continuous core magnetic field description over the entire time period 1999 to 2019.5 in good agreement with the CHAOS model series, but the addition of two new oceanic tidal magnetic sources: the larger lunar elliptic semi-diurnal constituent N_2 and the lunar diurnal constituent O_1. CM6 is also the parent model of the NASA/GSFC candidates for the DGRF2015 and IGRF2020 in response to the IGRF-13 call. This paper provides a full report on the development of CM6.

Keywords: Geomagnetism, Field modeling, CHAMP and Swarm satellites, Tides



Real (left) and imaginary (right) parts of the radial component of the N_2 oceanic tidal magnetic field at satellite altitude from CM6.

Graphical abstract

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FULL PAPER **Open Access**

A candidate secular variation model for IGRF-13 based on MHD dynamo simulation and 4DEnVar data assimilation

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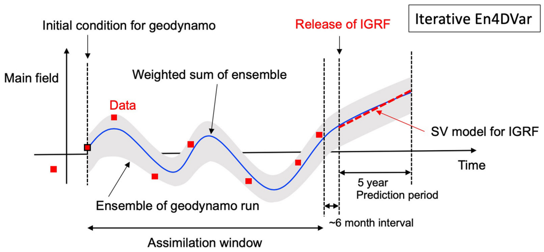
Abstract

We have submitted a secular variation (SV) candidate model for the thirteenth generation of International Geomagnetic Reference Field model (IGRF-13) using a data assimilation scheme and a magnetohydrodynamic (MHD) dynamo simulation code. This is the first contribution to the IGRF community from research groups in Japan. A geomagnetic field model derived from magnetic observatory hourly means, and CHAMP and Swarm-A satellite data, has been used as input data to the assimilation scheme. We adopt an ensemble-based assimilation scheme, called four-dimensional ensemble-based variational method (4DEnVar), which linearizes outputs of MHD dynamo simulation with respect to the deviation from a dynamo state vector at an initial condition. The data vector for the assimilation consists of the poloidal scalar potential of the geomagnetic field at the core surface and flow velocity field slightly below the core surface. Dimensionless time of numerical geodynamo is adjusted to the actual time by comparison of secular variation time scales. For SV prediction, we first generate an ensemble of dynamo simulation results from a free dynamo run. We then assimilate the ensemble to the data with a 10-year assimilation window through iterations, and finally forecast future SV by the weighted sum of the future extension parts of the ensemble members. Hindcast of the method for the assimilation window from 2004.50 to 2014.25 confirms that the linear approximation holds for 10-year assimilation window with our iterative ensemble renewal method. We demonstrate that the forecast performance of our data assimilation and forecast scheme is comparable with that of IGRF-12 by comparing data misfits 4.5 years after the release epoch. For estimation of our IGRF-13SV candidate model, we set assimilation window from 2009.50 to 2019.50. We generate our final SV candidate model by linear fitting for the weighted sum of the ensemble MHD dynamo simulation members from 2019.50 to 2025.00. We derive errors of our SV candidate model by one standard deviation of SV histograms based on all the ensemble members.

Keywords: IGRF, Secular variation, Geodynamo, Data assimilation, Core surface flow, 4DEnVar



Graphical abstract

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FULL PAPER **Open Access**

Forecasting yearly geomagnetic variation through sequential estimation of core flow and magnetic diffusion

Maurits C. Metman, Ciarán D. Beggan, Philip W. Livermore and Jonathan E. Mound*

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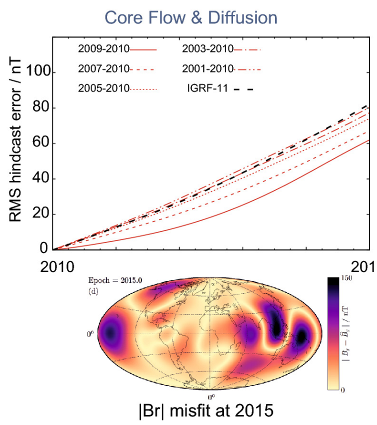
Abstract

Earth's internal magnetic field is generated through motion of the electrically conductive iron-alloy fluid comprising its outer core. Temporal variability of this magnetic field, termed secular variation (SV), results from two processes: one is the interaction between core fluid motion and the magnetic field, the other is magnetic diffusion. As diffusion is widely thought to take place over relatively long, millennial time scales, it is common to disregard it when considering yearly to decadal field changes; in this frozen-flux approximation, core fluid motion may be inferred on the core–mantle boundary (CMB) using observations of SV at Earth's surface. Such flow models have been used to forecast variation in the magnetic field. However, recent work suggests that diffusion may also contribute significantly to SV on short time scales provided that the radial length scale of the magnetic field structure within the core is sufficiently short. In this work, we introduce a hybrid method to forecast field evolution that considers a model based on both a steady flow and diffusion, in which we adopt a two-step process: first fitting the SV to a steady flow, and then fitting the residual by magnetic diffusion. We assess this approach by hindcasting the evolution for 2010–2015, based on fitting the models to CHAOS-6 using time windows prior to 2010. We find that including diffusion yields a reduction of up to 25% in the global hindcast error at Earth's surface; at the CMB this error reduction can be in excess of 77%. We show that fitting the model over the shortest window that we consider, 2009–2010, yields the lowest hindcast error. Based on our hindcast tests, we present a candidate model for the SV over 2020–2025 for IGRF-13, fit over the time window 2018.3–2019.3. Our forecasts indicate that over the next decade the axial dipole will continue to decay, reversed-flux patches will increase in both area and intensity, and the north magnetic (dip) pole will continue to migrate towards Siberia.

Keywords: Geomagnetism, Secular variation, Frozen flux, diffusion



Graphical abstract

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FULL PAPER Open Access

Bootstrapping *Swarm* and observatory data to generate candidates for the DGRF and IGRF-13

F. Javier Pavón-Carrasco*, Santiago Marsal, J. Miquel Torta, Manuel Catalán, Fátima Martín-Hernández and J. Manuel Tordesillas

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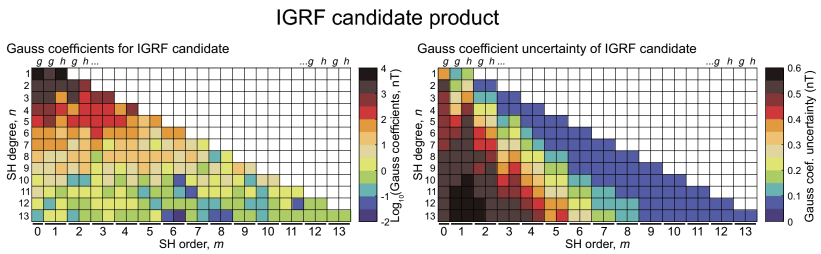
Abstract

As posted by the Working Group V of the International Association of Geomagnetism and Aeronomy (IAGA), the 13th generation of the International Geomagnetic Reference Field (IGRF) has been released at the end of 2019. Following IAGA recommendations, in this work we present a candidate model for the IGRF-13, for which we have used the available *Swarm* satellite and geomagnetic observatory ground data for the last year. In order to provide the IGRF-13 candidate, we have extrapolated the Gauss coefficients of the main field and its secular variation to January 1st, 2020. In addition, we have generated a Definitive Geomagnetic Reference Field model for 2015.0 using the same modelling approach, but focussed on a 1-year time window of data centred on 2015.0. To jointly model both satellite and ground data, we have followed the classical protocols and data filters applied in geomagnetic field modelling. Novelty arrives from the application of bootstrap analysis to solve issues related to the inhomogeneity of the spatial and temporal data distributions. This new approach allows the estimation of not only the Gauss coefficients, but also their uncertainties.

Keywords: Geomagnetic field, Geomagnetic field modelling, Secular variation, IGRF, *Swarm*, Geomagnetic observatories



Graphical abstract

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FULL PAPER Open Access

Sequential modelling of the Earth's core magnetic field

Guillaume Ropp*, Vincent Lesur, Julien Baerenzung and Matthias Holschneider

Earth, Planets and Space 2020, **72**:153 DOI: 10.1186/s40623-020-01230-1
Received: 19 March 2020, Accepted: 8 July 2020, Published: 21 October 2020

Abstract

We describe a new, original approach to the modelling of the Earth's magnetic field. The overall objective of this study is to reliably render fast variations of the core field and its secular variation. This method combines a sequential modelling approach, a Kalman filter, and a correlation-based modelling step. Sources that most significantly contribute to the field measured at the surface of the Earth are modelled. Their separation is based on strong prior information on their spatial and temporal behaviours. We obtain a time series of model distributions which display behaviours similar to those of recent models based on more classic approaches, particularly at large temporal and spatial scales. Interesting new features and periodicities are visible in our models at smaller time and spatial scales. An important aspect of our method is to yield reliable error bars for all model parameters. These errors, however, are only as reliable as the description of the different sources and the prior information used are realistic. Finally, we used a slightly different version of our method to produce candidate models for the thirteenth edition of the International Geomagnetic Reference Field.

Keywords: Geomagnetic field, Secular variation, Kalman filter, IGRF

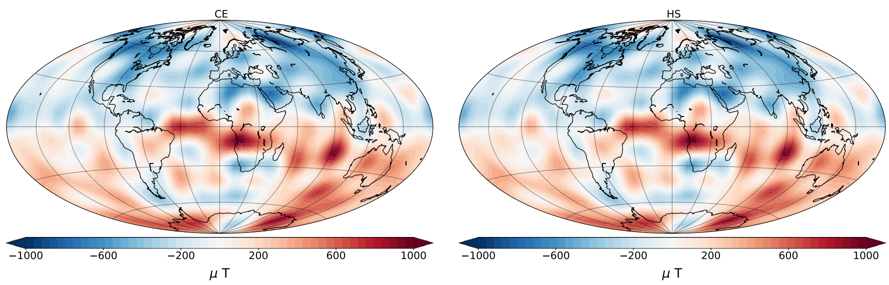

Fig. 1

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Geomagnetic core field models and secular variation forecasts for the 13th International Geomagnetic Reference Field (IGRF-13)

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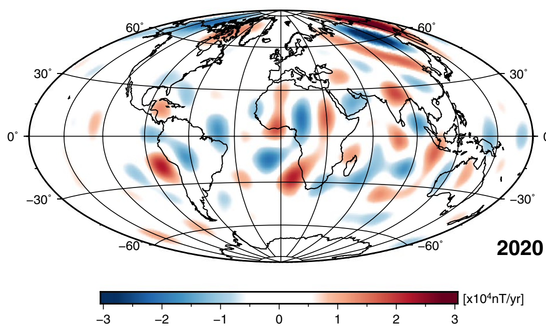
Earth, Planets and Space 2020, **72**:155 DOI: 10.1186/s40623-020-01254-7
Received: 30 April 2020, Accepted: 19 August 2020, Published: 22 October 2020

Abstract
Observations of the geomagnetic field taken at Earth's surface and at satellite altitude are combined to construct continuous models of the geomagnetic field and its secular variation from 1957 to 2020. From these parent models, we derive candidate main field models for the epochs 2015 and 2020 to the 13th generation of the International Geomagnetic Reference Field (IGRF). The secular variation candidate model for the period 2020–2025 is derived from a forecast of the secular variation in 2022.5, which results from a multi-variate singular spectrum analysis of the secular variation from 1957 to 2020.

Keywords: The geomagnetic field, Geomagnetic secular variation, Geomagnetic field models, Forecasts of the geomagnetic field



Graphical abstract

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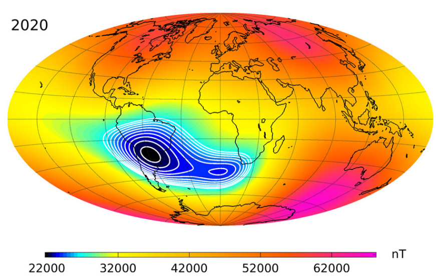
FULL PAPER **Open Access**

The CHAOS-7 geomagnetic field model and observed changes in the South Atlantic Anomaly

Christopher C. Finlay*, Clemens Kloss, Nils Olsen, Magnus D. Hammer, Lars Tøffner-Clausen, Alexander Grayver and Alexey Kuvshinov

Earth, Planets and Space 2020, **72**:156 DOI: 10.1186/s40623-020-01252-9
Received: 5 May 2020, Accepted: 17 August 2020, Published: 20 October 2020

Abstract
We present the CHAOS-7 model of the time-dependent near-Earth geomagnetic field between 1999 and 2020 based on magnetic field observations collected by the low-Earth orbit satellites *Swarm*, CryoSat-2, CHAMP, SAC-C and Ørsted, and on annual differences of monthly means of ground observatory measurements. The CHAOS-7 model consists of a time-dependent internal field up to spherical harmonic degree 20, a static internal field which merges to the LCS-1 lithospheric field model above degree 25, a model of the magnetospheric field and its induced counterpart, estimates of Euler angles describing the alignment of satellite vector magnetometers, and magnetometer calibration parameters for CryoSat-2. Only data from dark regions satisfying strict geomagnetic quiet-time criteria (including conditions on IMF B_z and B_y at all latitudes) were used in the field estimation. Model parameters were estimated using an iteratively reweighted regularized least-squares procedure; regularization of the time-dependent internal field was relaxed at high spherical harmonic degree compared with previous versions of the CHAOS model. We use CHAOS-7 to investigate recent changes in the geomagnetic field, studying the evolution of the South Atlantic weak field anomaly and rapid field changes in the Pacific region since 2014. At Earth's surface a secondary minimum of the South Atlantic Anomaly is now evident to the south west of Africa. Green's functions relating the core–mantle boundary radial field to the surface intensity show this feature is connected with the movement and evolution of a reversed flux feature under South Africa. The continuing growth in size and weakening of the main anomaly is linked to the westward motion and gathering of reversed flux under South America. In the Pacific region at Earth's surface between 2015 and 2018 a sign change has occurred in the second time derivative (acceleration) of the radial component of the field. This acceleration change took the form of a localized, east–west oriented, dipole. It was clearly recorded on ground, for example at the magnetic observatory at Honolulu, and was seen in *Swarm* observations over an extended region in the central and western Pacific. Downward continuing to the core–mantle boundary, we find this event originated in field acceleration changes at low latitudes beneath the central and western Pacific in 2017.



Graphical abstract

Keywords: Geomagnetism, Secular variation, Field modelling, South Atlantic Anomaly, *Swarm*

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FULL PAPER Open Access

Predictions of the geomagnetic secular variation based on the ensemble sequential assimilation of geomagnetic field models by dynamo simulations

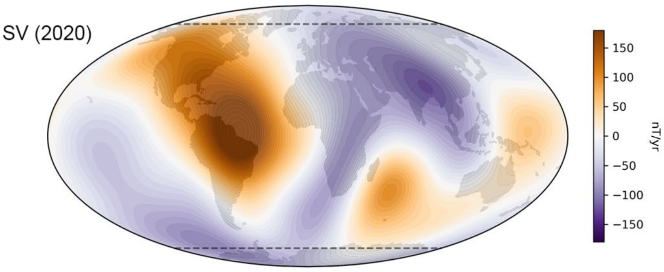
Sabrina Sanchez*, Johannes Wicht and Julien Bärenzung

Earth, Planets and Space 2020, **72**:157 DOI: 10.1186/s40623-020-01279-y
Received: 17 April 2020, Accepted: 23 September 2020, Published: 22 October 2020

Abstract

The IGRF offers an important incentive for testing algorithms predicting the Earth's magnetic field changes, known as secular variation (SV), in a 5-year range. Here, we present a SV candidate model for the 13th IGRF that stems from a sequential ensemble data assimilation approach (EnKF). The ensemble consists of a number of parallel-running 3D-dynamo simulations. The assimilated data are geomagnetic field snapshots covering the years 1840 to 2000 from the COV-OBS.x1 model and for 2001 to 2020 from the Kalmag model. A spectral covariance localization method, considering the couplings between spherical harmonics of the same equatorial symmetry and same azimuthal wave number, allows decreasing the ensemble size to about a 100 while maintaining the stability of the assimilation. The quality of 5-year predictions is tested for the past two decades. These tests show that the assimilation scheme is able to reconstruct the overall SV evolution. They also suggest that a better 5-year forecast is obtained keeping the SV constant compared to the dynamically evolving SV. However, the quality of the dynamical forecast steadily improves over the full assimilation window (180 years). We therefore propose the instantaneous SV estimate for 2020 from our assimilation as a candidate model for the IGRF-13. The ensemble approach provides uncertainty estimates, which closely match the residual differences with respect to the IGRF-13. Longer term predictions for the evolution of the main magnetic field features over a 50-year range are also presented. We observe the further decrease of the axial dipole at a mean rate of 8 nT/year as well as a deepening and broadening of the South Atlantic Anomaly. The magnetic dip poles are seen to approach an eccentric dipole configuration.

Keywords: Earth's magnetic field, Geomagnetic secular variation, Dynamo simulations, Data assimilation



Graphical abstract

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FULL PAPER Open Access

COV-OBS.x2: 180 years of geomagnetic field evolution from ground-based and satellite observations

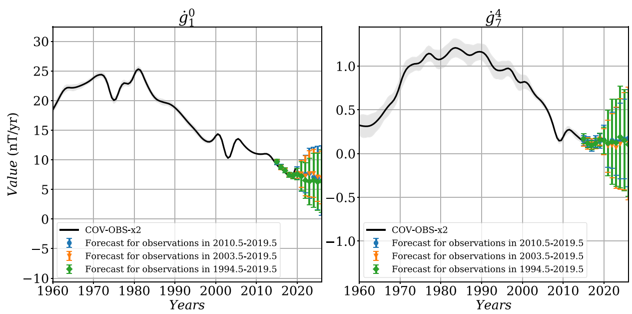
Loïc Huder, Nicolas Gillet*, Christopher C. Finlay, Magnus D. Hammer and Hervé Tchoungui

Earth, Planets and Space 2020, **72**:160 DOI: 10.1186/s40623-020-01194-2
Received: 4 February 2020, Accepted: 8 May 2020, Published: 23 October 2020

Abstract

We present the geomagnetic field model COV-OBS.x2 that covers the period 1840–2020. It is primarily constrained by observatory series, satellite data, plus older surveys. Over the past two decades, we consider annual differences of 4-monthly means at ground-based stations (since 1996), and virtual observatory series derived from magnetic data of the satellite missions CHAMP (over 2001–2010) and Swarm (since 2013). A priori information is needed to complement the constraints carried by geomagnetic records and solve the ill-posed geomagnetic inverse problem. We use for this purpose temporal cross-covariances associated with auto-regressive stochastic processes of order 2, whose parameters are chosen so as to mimic the temporal power spectral density observed in paleomagnetic and observatory series. We aim this way to obtain as far as possible realistic posterior model uncertainties. These can be used to infer for instance the core dynamics through data assimilation algorithms, or an envelope for short-term magnetic field forecasts. We show that because of the projection onto splines, one needs to inflate the formal model error variances at the most recent epochs, in order to account for unmodeled high frequency core field changes. As a by-product of the core field model, we co-estimate the external magnetospheric dipole evolution on periods longer than 2 years. It is efficiently summarized as the sum of a damped oscillator (of period 10.5 years and decay rate 55 years), plus a short-memory (6 years) damped random walk.

Keywords: Geomagnetic field, Secular variation, Stochastic equations, Model uncertainties



Graphical abstract

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FULL PAPER **Open Access**

The Kalmag model as a candidate for IGRF-13

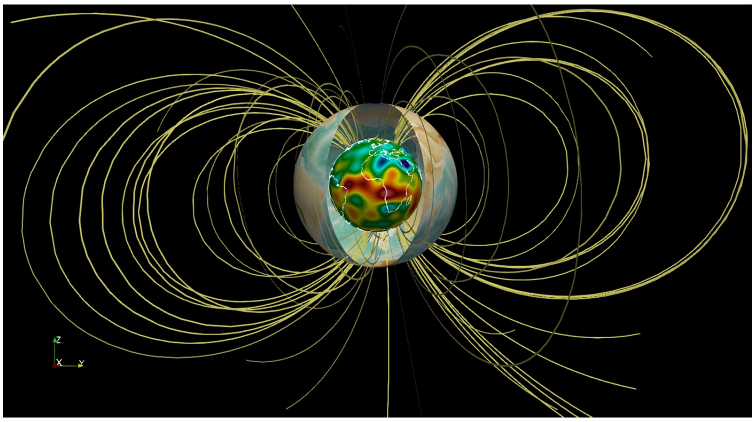
Julien Baerenzung*, Matthias Holschneider, Johannes Wicht, Vincent Lesur and Sabrina Sanchez

Earth, Planets and Space 2020, **72**:163 DOI: 10.1186/s40623-020-01295-y
Received: 24 June 2020, Accepted: 13 October 2020, Published: 29 October 2020

Abstract

We present a new model of the geomagnetic field spanning the last 20 years and called Kalmag. Deriving from the assimilation of CHAMP and Swarm vector field measurements, it separates the different contributions to the observable field through parameterized prior covariance matrices. To make the inverse problem numerically feasible, it has been sequentialized in time through the combination of a Kalman filter and a smoothing algorithm. The model provides reliable estimates of past, present and future mean fields and associated uncertainties. The version presented here is an update of our IGRF candidates; the amount of assimilated data has been doubled and the considered time window has been extended from [2000.5, 2019.74] to [2000.5, 2020.33].

Keywords: Geomagnetic field, Secular variation, Assimilation, Kalman filter, Machine learning



Graphical abstract

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FULL PAPER **Open Access**

The BGS candidate models for IGRF-13 with a retrospective analysis of IGRF-12 secular variation forecasts

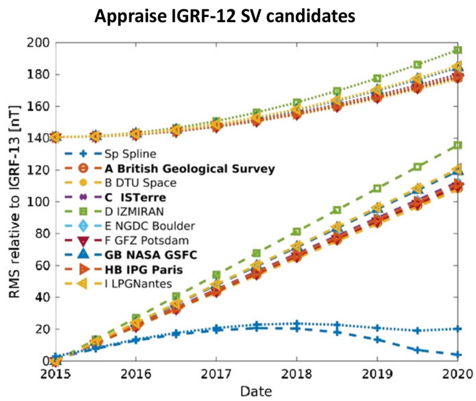
William J. Brown*, Ciarán D. Beggan, Grace A. Cox and Susan Macmillan

Earth, Planets and Space 2021, **73**:42 DOI: 10.1186/s40623-020-01301-3
Received: 19 May 2020, Accepted: 22 October 2020, Published: 11 February 2021

Abstract

The three candidate models submitted by the British Geological Survey for the 13th generation International Geomagnetic Reference Field are described. These DGRF and IGRF models are derived from vector and scalar magnetic field data from the European Space Agency Swarm satellites and ground observatories, covering the period 2013.9 to 2019.7. The internal field model has time dependence for degrees 1 to 15, represented by order 6 B-splines with knots at six monthly intervals. We also solve for a degree 1 external field time dependence describing annual and semi-annual signals with additional dependence on a bespoke Vector Magnetic Disturbance index. Satellite data are weighted by spatial density, along-track standard deviations, and a larger-scale noise estimator defined in terms of a measure of Local Area Vector Activity at the geographically closest magnetic observatories to the sampled datum. Forecasting of the magnetic field secular variation for 2020–2025 is by advection of the main field using steady core surface flows with steady acceleration applied. We also investigate the performance of the previous generation of candidate secular variation models, for IGRF-12, analysing the agreement of the candidates between 2015 and 2020 with the retrospective IGRF-13. We find that there is no clear distinction between the performance of mathematically and physically extrapolated forecasts in the period 2015–2020. We confirm that the methodology for the BGS IGRF-12 predictions performed well, despite observed secular accelerations that are highlighted by our analysis, and thus justify the methodology used for our IGRF-13 SV candidate.

Keywords: International Geomagnetic Reference Field, Geomagnetism, Secular variation



Graphical abstract

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A secular variation candidate model for IGRF-13 based on Swarm data and ensemble inverse geodynamo modelling

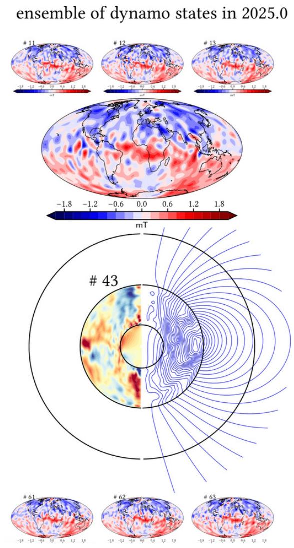
Alexandre Fournier*, Julien Aubert, Vincent Lesur and Guillaume Ropp

Earth, Planets and Space 2021, **73**:43 DOI: 10.1186/s40623-020-01309-9
Received: 31 January 2020, Accepted: 5 November 2020, Published: 11 February 2021

Abstract

This paper describes the design of a candidate secular variation model for the 13th generation of the International Geomagnetic Reference Field. This candidate is based upon the integration of an ensemble of 100 numerical models of the geodynamo between epochs 2019.0 and 2025.0. The only difference between each ensemble member lies in the initial condition that is used for the numerical integration, all other control parameters being fixed. An initial condition is defined as follows: an estimate of the magnetic field and its rate-of-change at the core surface for 2019.0 is obtained from a year (2018.5–2019.5) of vector Swarm data. This estimate (common to all ensemble members) is subject to prior constraints: the statistical properties of the numerical dynamo model for the main geomagnetic field and its secular variation, and prescribed covariances for the other sources. One next considers 100 three-dimensional core states (in terms of flow, buoyancy and magnetic fields) extracted at different discrete times from a dynamo simulation that is not constrained by observations, with the time distance between each state exceeding the dynamo decorrelation time. Each state is adjusted (in three dimensions) in order to take the estimate of the geomagnetic field and its rate-of-change for 2019.0 into account. This methodology provides 100 different initial conditions for subsequent numerical integration of the dynamo model up to epoch 2025.0. Focussing on the 2020.0–2025.0 time window, we use the median average rate-of-change of each Gauss coefficient of the ensemble and its statistics to define the geomagnetic secular variation over that time frame and its uncertainties.

Keywords: Earth's magnetic field, Geomagnetic secular variation, Satellite magnetics, Dynamo: theory and simulation, Inverse theory



Graphical abstract

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FULL PAPER Open Access

NOAA/NCEI and University of Colorado candidate models for IGRF-13

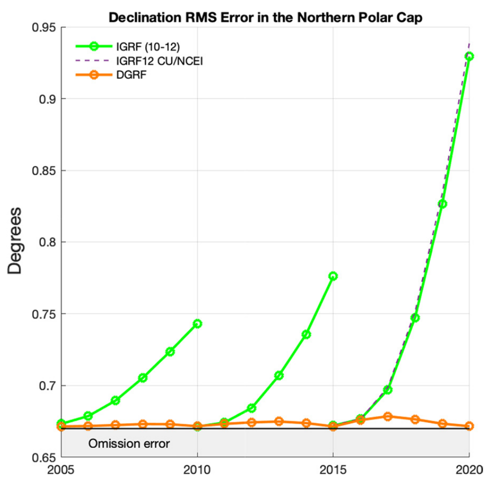
P. Alken*, A. Chulliat and M. Nair

Earth, Planets and Space 2021, **73**:44 DOI: 10.1186/s40623-020-01313-z
Received: 7 September 2020, Accepted: 10 November 2020, Published: 11 February 2021

Abstract

The International Geomagnetic Reference Field (IGRF) is a set of parameters representing the large-scale internal part of Earth's magnetic field. The 13th generation IGRF requested candidate models for a definitive main field for 2015.0, a provisional main field for 2020.0, and a predictive secular variation covering the period 2020.0–2025.0. The University of Colorado (CU) and the National Centers for Environmental Information (NCEI), part of the National Oceanic and Atmospheric Administration (NOAA), have produced these three candidate models for consideration in IGRF-13. In this paper, we present the methodology used to derive our candidate models. Our candidates were built primarily from Swarm satellite data, and also relied on geomagnetic indices derived from the ground observatory network. The ground observatories played a crucial role as independent data in validating our candidates. This paper also provides a retrospective assessment of the CU/NCEI candidate model to the previous IGRF (IGRF-12) and discusses the impact of differences between candidate and final IGRF models on global model errors.

Keywords: IGRF, Magnetic field modeling, Geomagnetism



Graphical abstract

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FULL PAPER Open Access

The CSES global geomagnetic field model (CGGM): an IGRF-type global geomagnetic field model based on data from the China Seismo-Electromagnetic Satellite

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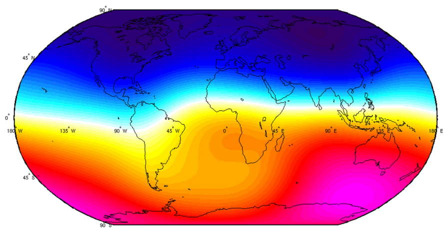
Abstract

Using magnetic field data from the China Seismo-Electromagnetic Satellite (CSES) mission, we derive a global geomagnetic field model, which we call the CSES Global Geomagnetic Field Model (CGGM). This model describes the Earth's magnetic main field and its linear temporal evolution over the time period between March 2018 and September 2019. As the CSES mission was not originally designed for main field modelling, we carefully assess the ability of the CSES orbits and data to provide relevant data for such a purpose. A number of issues are identified, and an appropriate modelling approach is found to mitigate these. The resulting CGGM model appears to be of high enough quality, and it is next used as a parent model to produce a main field model extrapolated to epoch 2020.0, which was eventually submitted on October 1, 2019 as one of the IGRF-13 2020 candidate models. This CGGM candidate model, the first ever produced by a Chinese-led team, is also the only one relying on a data set completely independent from that used by all other candidate models. A successful validation of this candidate model is performed by comparison with the final (now published) IGRF-13 2020 model and all other candidate models. Comparisons of the secular variation predicted by the CGGM parent model with the final IGRF-13 2020–2025 predictive secular variation also reveal a remarkable agreement. This shows that, despite their current limitations, CSES magnetic data can already be used to produce useful IGRF 2020 and 2020–2025 secular variation candidate models to contribute to the official IGRF-13 2020 and predictive secular variation models for the coming 2020–2025 time period. These very encouraging results show that additional efforts to improve the CSES magnetic data quality could make these data very useful for long-term monitoring of the main field and possibly other magnetic field sources, in complement to the data provided by missions such as the ESA Swarm mission.



Graphical abstract

Keywords: CSES, CGGM, IGRF, Geomagnetism, Space magnetometry

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FULL PAPER Open Access

Geomagnetic secular variation forecast using the NASA GEMS ensemble Kalman filter: A candidate SV model for IGRF-13

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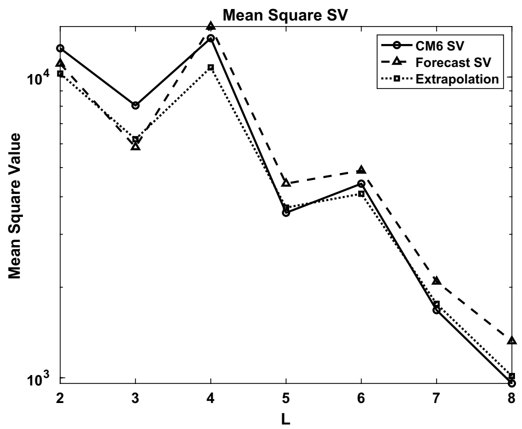
Earth, Planets and Space 2021, **73**:47 DOI: 10.1186/s40623-020-01324-w
Received: 22 July 2020, Accepted: 27 November 2020, Published: 11 February 2021

Abstract

We have produced a 5-year mean secular variation (SV) of the geomagnetic field for the period 2020–2025. We use the NASA Geomagnetic Ensemble Modeling System (GEMS), which consists of the NASA Goddard geodynamo model and ensemble Kalman filter (EnKF) with 400 ensemble members. Geomagnetic field models are used as observations for the assimilation, including *gufm1* (1590–1960), CM4 (1961–2000) and CM6 (2001–2019). The forecast involves a bias correction scheme that assumes that the model bias changes on timescales much longer than the forecast period, so that they can be removed by successive forecast series. The algorithm was validated on the time period 2010-2015 by comparing with CM6 before being applied to the 2020–2025 time period. This forecast has been submitted as a candidate predictive model of IGRF-13 for the period 2020–2025.

Keywords: Geomagnetic Secular Variation, Data Assimilation, Geodynamo Model



Graphical abstract

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International Geomagnetic Reference Field: the thirteenth generation

P. Alken*, E. Thébault, C. D. Beggan, H. Amit, J. Aubert, J. Baerenzung, T. N. Bondar, W. J. Brown, S. Califf, A. Chambodut, A. Chulliat, G. A. Cox, C. C. Finlay, A. Fournier, N. Gillet, A. Grayver, M. D. Hammer, M. Holschneider, L. Huder, G. Hulot, T. Jager, C. Kloss, M. Korte, W. Kuang, A. Kuvshinov, B. Langlais, J.-M. Léger, V. Lesur, P. W. Livermore, F. J. Lowes, S. Macmillan, W. Magnes, M. Mandea, S. Marsal, J. Matzka, M. C. Metman, T. Minami, A. Morschhauser, J. E. Mound, M. Nair, S. Nakano, N. Olsen, F. J. Pavón-Carrasco, V. G. Petrov, G. Ropp, M. Rother, T. J. Sabaka, S. Sanchez, D. Saturnino, N. R. Schnepf, X. Shen, C. Stolle, A. Tangborn, L. Tøffner-Clausen, H. Toh, J. M. Torta, J. Varner, F. Vervelidou, P. Vigneron, I. Wardinski, J. Wicht, A. Woods, Y. Yang, Z. Zeren and B. Zhou

Earth, Planets and Space 2021, **73**:49 DOI: 10.1186/s40623-020-01288-x
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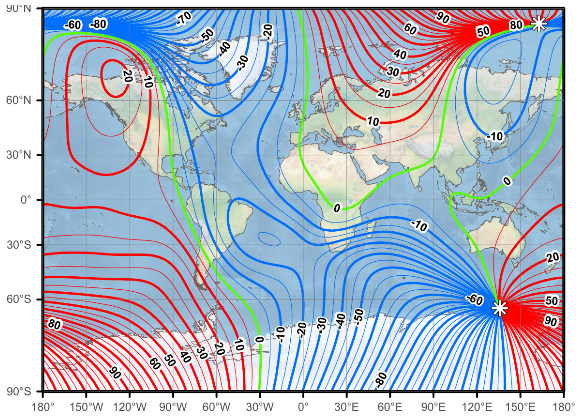
Abstract

In December 2019, the International Association of Geomagnetism and Aeronomy (IAGA) Division V Working Group (V-MOD) adopted the thirteenth generation of the International Geomagnetic Reference Field (IGRF). This IGRF updates the previous generation with a definitive main field model for epoch 2015.0, a main field model for epoch 2020.0, and a predictive linear secular variation for 2020.0 to 2025.0. This letter provides the equations defining the IGRF, the spherical harmonic coefficients for this thirteenth generation model, maps of magnetic declination, inclination and total field intensity for the epoch 2020.0, and maps of their predicted rate of change for the 2020.0 to 2025.0 time period.

Keywords: IGRF, Magnetic field modeling, Geomagnetism



Graphical abstract

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FULL PAPER Open Access

The `Mag.num` core field model as a parent for IGRF-13, and the recent evolution of the South Atlantic Anomaly

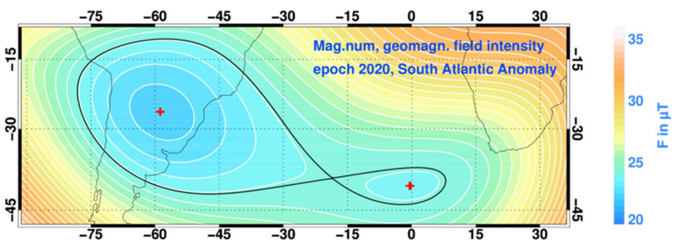
M. Rother*, M. Korte, A. Morschhauser, F. Vervelidou, J. Matzka and C. Stolle

Earth, Planets and Space 2021, **73**:50 DOI: 10.1186/s40623-020-01277-0
Received: 30 April 2020, Accepted: 20 September 2020, Published: 11 February 2021

Abstract

We present the GFZ candidate field models for the 13th Generation International Geomagnetic Reference Field (IGRF-13). These candidates were derived from the `Mag.num.IGRF13` geomagnetic core field model, which is constrained by Swarm satellite and ground observatory data from November 2013 to August 2019. Data were selected from magnetically quiet periods, and the model parameters have been obtained using an iteratively reweighted inversion scheme approximating a robust modified Huber norm as a measure of misfit. The root mean square misfit of the `Mag.num.IGRF13` model to Swarm and observatory data is in the order of 3–5 nT for mid and low latitudes, with a maximum of 44 nT for the satellite east component data at high latitudes. The time-varying core field is described by order 6 splines and spherical harmonic coefficients up to degree and order 20. We note that the temporal variation of the core field component of the `Mag.num.IGRF13` model is strongly damped and shows a smooth secular variation that suits well for the IGRF, where secular variation is represented as constant over 5-year intervals. Further, the external field is parameterised by a slowly varying part and a more rapidly varying part controlled by magnetic activity and interplanetary magnetic field proxies. Additionally, the Euler angles of the magnetic field sensor orientation are co-estimated. A widely discussed feature of the geomagnetic field is the South Atlantic Anomaly, a zone of weak and decreasing field strength stretching from southern Africa over to South America. The IGRF and `Mag.num.IGRF13` indicate that the anomaly has developed a second, less pronounced eastern minimum at Earth's surface since 2007. We observe that while the strong western minimum continues to drift westwards, the less pronounced eastern minimum currently drifts eastward at Earth's surface. This does not seem to be linked to any eastward motion at the core–mantle boundary, but rather to intensity changes of westward drifting flux patches contributing to the observed surface field. Also, we report a sudden change in the secular variation measured at two South Atlantic observatories around 2015.0, which occurred shortly after the well-known jerk of 2014.0.

Keywords: Geomagnetic field model, Main magnetic field, South Atlantic Anomaly, Swarm, IGRF



Graphical abstract

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EXPRESS LETTER **Open Access**

IZMIRAN candidate field model for IGRF-13

Valeriy G. Petrov* and Tatyana N. Bondar

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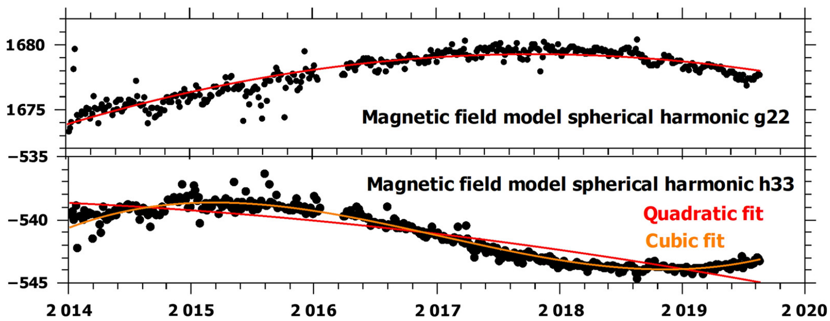
Abstract

The International Geomagnetic Reference Field (IGRF) model is a combination of the several models developed by independent groups of scientists using different approaches for the selection of input data and methods for calculating harmonic coefficients. This approach allows for mutual comparison of individual models and for their combination to obtain the most reliable values of the harmonic coefficients. This letter provides a brief description of methods for building the IZMIRAN Earth's main magnetic field model, submitted to the IAGA Working Group V-MOD for creating IGRF-13. Special efforts were made to obtain as uniform coverage of the entire Earth's surface as possible with observations. The surface was divided into a grid of approximately equal cells. Then the data for geomagnetically quiet intervals were placed in the corresponding cells and a median filter was applied to select the data in each cell. Spherical harmonic coefficients up to degree 13 were calculated for the interval 2014-Jan to 2019-Aug with a time step of 10 days and extrapolated to 01.01.2010.

Keywords: IGRF, Magnetic field modeling, Geomagnetism



Graphical abstract

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EXPRESS LETTER **Open Access**

Using improved Swarm's experimental absolute vector mode data to produce a candidate Definitive Geomagnetic Reference Field (DGRF) 2015.0 model

Pierre Vigneron, Gauthier Hulot*, Jean-Michel Léger and Thomas Jager

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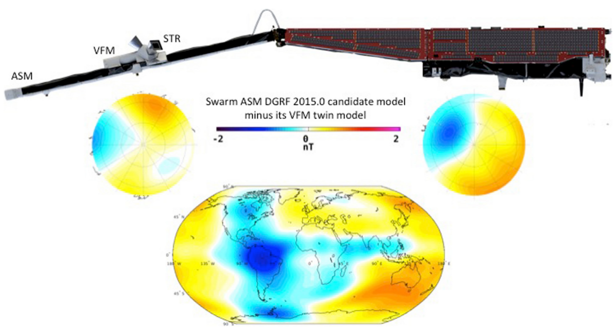
Abstract

We describe the way a global model of the geomagnetic field has been built using vector field data acquired by the absolute scalar magnetometers (ASM) running in vector mode on board the Alpha and Bravo satellites of the European Space Agency (ESA) Swarm mission. This model has been used as a parent model to build a candidate Definitive Geomagnetic Reference Field (DGRF) 2015.0 model to meet the call issued in the context of the recent update of the International Geomagnetic Reference Field (IGRF thirteenth generation). Because small but systematic issues were identified in a previous candidate IGRF 2015.0 model built in the same spirit (also only relying on ASM vector field data) in the context of the previous IGRF update (IGRF twelfth generation), we now also use improved ASM vector field (ASM-V) data. The issue originally affecting the ASM-V data is described, together with the way the improved data are now being produced. The resulting candidate DGRF 2015.0 model is shown to considerably improve on the previous candidate IGRF 2015.0 model (being closer to the final DGRF 2015.0 model by one order of magnitude in spherical harmonic spectral terms). It is also shown to stand among the candidate models closest to the final official DGRF 2015.0 model. Being the only candidate DGRF 2015.0 model entirely and only relying on such ASM-V data, it demonstrates the value of the new ASM-V data for such global geomagnetic field modeling purposes.

Keywords: Geomagnetism, Magnetic field modeling, IGRF, Swarm mission, Absolute vector magnetometers



Graphical abstract

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TECHNICAL REPORT
Open Access

Evaluation of candidate models for the 13th generation International Geomagnetic Reference Field

P. Alken, E. Thébault*, C. D. Beggan, J. Aubert, J. Baerenzung, W. J. Brown, S. Califf, A. Chulliat, G. A. Cox, C. C. Finlay, A. Fournier, N. Gillet, M. D. Hammer, M. Holschneider, G. Hulot, M. Korte, V. Lesur, P. W. Livermore, F. J. Lowes, S. Macmillan, M. Nair, N. Olsen, G. Ropp, M. Rother, N. R. Schnepf, C. Stolle, H. Toh, F. Vervelidou, P. Vigneron and I. Wardinski

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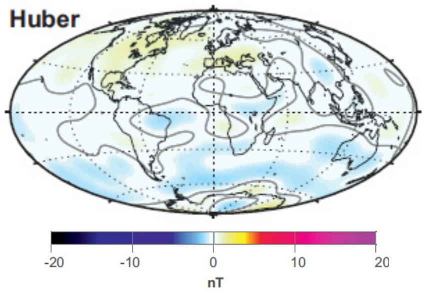
Abstract

In December 2019, the 13th revision of the International Geomagnetic Reference Field (IGRF) was released by the International Association of Geomagnetism and Aeronomy (IAGA) Division V Working Group V-MOD. This revision comprises two new spherical harmonic main field models for epochs 2015.0 (DGRF-2015) and 2020.0 (IGRF-2020) and a model of the predicted secular variation for the interval 2020.0 to 2025.0 (SV-2020-2025). The models were produced from candidates submitted by fifteen international teams. These teams were led by the British Geological Survey (UK), China Earthquake Administration (China), Universidad Complutense de Madrid (Spain), University of Colorado Boulder (USA), Technical University of Denmark (Denmark), GFZ German Research Centre for Geosciences (Germany), Institut de physique du globe de Paris (France), Institut des Sciences de la Terre (France), Pushkov Institute of Terrestrial Magnetism, Ionosphere and Radio Wave Propagation (Russia), Kyoto University (Japan), University of Leeds (UK), Max Planck Institute for Solar System Research (Germany), NASA Goddard Space Flight Center (USA), University of Potsdam (Germany), and Université de Strasbourg (France). The candidate models were evaluated individually and compared to all other candidates as well to the mean, median and a robust Huber-weighted model of all candidates. These analyses were used to identify, for example, the variation between the Gauss coefficients or the geographical regions where the candidate models strongly differed. The majority of candidates were sufficiently close that the differences can be explained primarily by individual modeling methodologies and data selection strategies. None of the candidates were so different as to warrant their exclusion from the final IGRF-13. The IAGA V-MOD task force thus voted for two approaches: the median of the Gauss coefficients of the candidates for the DGRF-2015 and IGRF-2020 models and the robust Huber-weighted model for the predictive SV-2020-2025. In this paper, we document the evaluation of the candidate models and provide details of the approach used to derive the final IGRF-13 products. We also perform a retrospective analysis of the IGRF-12 SV candidates over their performance period (2015–2020). Our findings suggest that forecasting secular variation can benefit from combining physics-based core modeling with satellite observations.



Graphical abstract

Keywords: IGRF, Magnetic field modeling, Geomagnetism

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Contents

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