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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

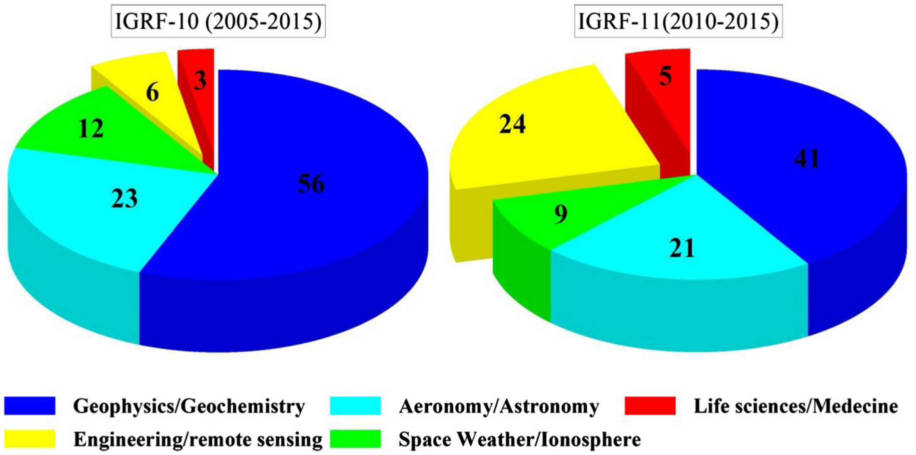

Fig. 1 Percentage by category of science papers citing the IGRF-10 between 2005 and 2015 (*left*) and citing the IGRF-11 paper between 2010 and 2015 (*right*)

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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