

GRIMM-2: The parent magnetic field model for an IGRF candidate model

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Abstract

The International Geomagnetic Reference Field (IGRF) is a very frequently used model of the Earth's main magnetic field by both the science community and the industry. This model is updated every five years. We present here the second generation of the GRIMM magnetic field model that was derived to contribute to the IGRF-11. The model has been developed from a newly, reprocessed CHAMP satellite data set covering nearly 10 years. It has a temporal and spatial resolution significantly improved compared to previous models.

1. Introduction

The CHAMP satellite has provided very high quality vector measurements of the Earth's magnetic field, which have led into numerous studies about its external and internal sources. In 2009, the satellite has been orbiting at very low altitude (around 320km), and, because the external magnetic field perturbations have been small due to a very long period of low solar activity, this has been particularly beneficial for studies of internal fields. Furthermore, fully processed CHAMP vector data have been made available up to 2009.5, in order to provide the best possible data set for the preparation of the 11th version of the International Geomagnetic Reference Field, IGRF (Finlay *et al.*, 2010).

The IGRF is a model of the main Earth's magnetic field that is made of a series of single epoch snapshot models, five years apart, and a predictive Secular Variation (SV) model. For the preparation of the new version of the IGRF, different institutes over the world have been pro-

posing candidates to the 2005 and 2010 snapshot field models and for the SV predictive model covering the epochs 2010-2015. In our case, these candidates have been derived from a parent model: the second version of the GFZ reference internal magnetic model --GRIMM-2 (Lesur *et al.*, 2010).

The Earth's core magnetic field is the most significant source of the Earth's main field. The contribution from the large-scale lithospheric field, although it cannot be separated from the core field contribution by analyzing magnetic data alone, is generally assumed to be negligible for the largest wavelength of the observed field. In the following we will therefore not distinguish between »core« and »main« magnetic fields.

We present in this manuscript some aspects of the second generation of the GRIMM model and the associated candidates to the IGRF. The main difficulty in building models of the Earth's main magnetic field is to deal with the other source contributions to the data. For main field modeling, these contributions are mainly those of the large-scale external field of magnetospheric origin, and the field generated at high latitudes in the polar ionosphere. The fields generated at mid latitudes in the dayside ionosphere are vanishing at night time (their induced internal counterparts are however persisting during the night). These mid-latitude ionospheric fields can therefore be ignored if night time data are used. To avoid as much as possible the leakage of other ionospheric and magnetospheric contributions into core magnetic field models, the only solution lies in

a careful data selection and appropriate modeling techniques. The GRIMM magnetic field model is based on a new approach of the data selection that has proved to lead to robust model of the Earth's main magnetic field.

We start in the next section in presenting some aspects of the data processing and its recent developments. Then, in the third section, elements of the GRIMM-2 model are presented. Finally, the fourth section is dedicated to the derivation of the IGRF candidates. We conclude in the last section.

2. Developments in the CHAMP magnetic field data processing

The main developments in terms of data processing have been made to improve the algorithm for the precise attitude determination of the magnetometers. In order to take full advantage of the fluxgate resolution, attitude knowledge with an arc-second precision is required. The scheme can be divided into three parts: First, the initial In-flight-Calibration procedure and the Star Camera (ASC) standard processing have been partly recoded, migrated to a new operating system, and upgraded by correlating irregularities with satellite house-keeping readings and other recorded external events. Second, the transformation routine from satellite into the Earth-Centered-Earth-Fixed (ECEF) NEC (North-East-Center) system has been improved, and validated. Last, the time series describing the observed bending of the optical bench (i.e. variation of the Euler Angles between magnetometer and ASC reference frame) has been validated by an independent modeling approach that co-estimates the time dependent Euler Angles and magnetic model coefficients. Further details are given below.

The original standard version of the ASC processing is leading to the CH-ME-2-ASC-BOOM products. The improvement of this ASC processing is still ongoing, but re-coding and migration to a new platform is finished. Additionally, considering data from the second pair

of ASC sensors in CHAMP's body, during this ASC processing, permits most of the time to control the results, but sometimes also filling the data gaps.

A validation of the initial transformation from the ASC-sensor to the ECEF coordinate system by an alternative computing path using an external astronomical library -- the »SOFA« library (IAU SOFA Center, 2010) -- was successfully done. Another step towards a robust processing to hold the precision of the attitude information was to overcome the discontinuation of the Bulletin B of the International Earth Rotation and Reference Systems Service (IERS Message 144). The integration of slightly different earth rotation parameters from the Bulletin B into the processing was done and was adopted as new standards.

For the validation of the time dependent Euler Angle a new, quaternion based, approach where a magnetic field model and the angles are co-estimated, was developed, coded, and tested on synthetic data. The approach has been also tested on real CHAMP data products and compared with solutions from other modeling groups. The new approach has proved to converge faster than an algorithm directly based on the angles. The quaternion-based algorithm benefits from the fairly simple form of the Hessian matrix. The field-modeling algorithm, on which this approach was developed, is the GRIMM inversion family algorithm.

Figure-1 shows that the GRIMM based Euler Angle estimation provide consistent results for various evaluation window lengths and data sets (i.e. either complete data set or selected data set). These results are also inside the expected deviation from the Euler Angle reference. This agreement is somewhat weakened for the early, more disturbed periods (see left frame in Figure-1 where a phase shift appears. This phase shift is not yet well understood and is under further investigation).

The determination of Euler Angle rotations in the framework of the CHAMP data processing

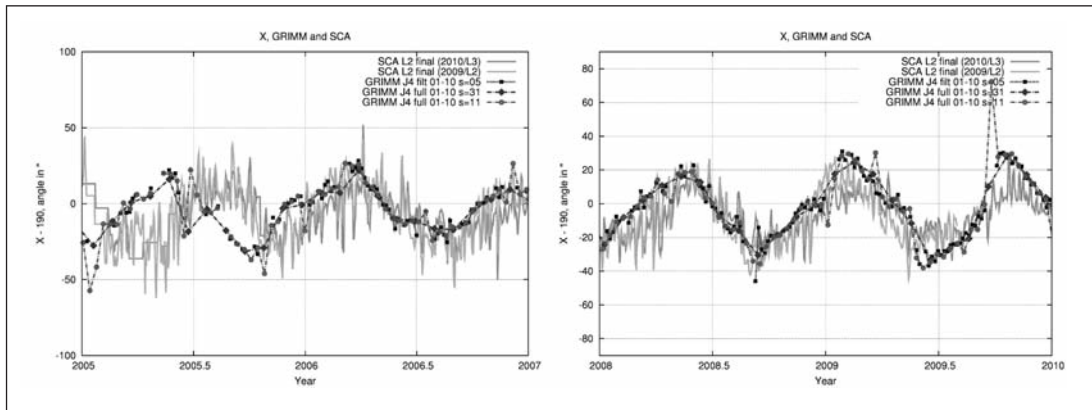


Figure 1: Late period of CHAMP mission period with SCA (POMME family based, personal communication with Stefan Maus) Euler Angle estimation (Gray, 2009 and 2010 version) compared with the newly developed, GRIMM based approach with various window sizes.

is a decisive step towards the challenging data processing of the multi-satellite ESA mission Swarm. The implementation can take data from other sources than CHAMP readings into account, either observatory data, as already tested, or other satellites (as required option for the multi-satellite Swarm project ahead).

The end of the active mission of CHAMP in September 19, 2010 triggered the preparations for the first full reprocessing of the vector magnetic field data with the currently available stage of the processing functionality.

3. The GRIMM-2 model

The model GRIMM-2 has been built from CHAMP satellite magnetic vector data only, and observatory hourly mean vector data. The version 51 Level-2 CHAMP satellite data set has been used. It spans the epochs 2001.0 to 2009.58 and includes improved time dependent FGM-ASC orientation corrections (i.e. orientation of the fluxgate magnetometers relative to the reference frame defined by the star cameras). The observatory hourly mean data have been used only up to 2009.0.

The data selection process differs depending on the data latitude. At mid and low latitudes, data are selected for magnetically quiet times as characterized by magnetic indices, night times, and X,Y components only in the Solar-Magnetic (SM) system of coordinates. At high

latitudes, the magnetic data are selected also for magnetically quiet periods, but at all local times, and for all three components in the usual North, East, Down (NEC) system of coordinates. It has been shown that such a selection technique leads to robust models of the core magnetic field. The underlying ideas are:

- 1) Not to use, at mid latitudes, data along the magnetic dipole axis (Z-SM axis) in order to avoid the magnetospheric dominant contributions generally attributed to the ring current.
- 2) Using all local time data at high latitudes to avoid large data gaps associated with the 6 month long summer day-light periods over the auroral regions.

The model parameterization includes a large-scale field of internal origin – i.e. the core field, the lithospheric field up wavelengths around 800km, and a large-scale external field with its associated induced counterpart. The core field is parameterized in time using B-splines of order six. The lithospheric field is assumed constant in time whereas the external field is parameterized in time by piece-wise linear polynomials, with knots three months apart. This is completed, for the rapid temporal variations of the external field and their induced counterparts, by a parameterization based on the VMD index (Thomson and Lesur, 2007).

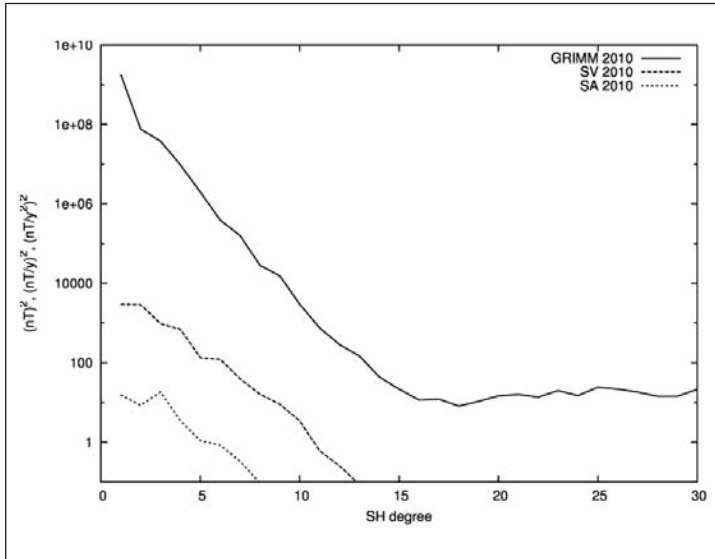


Figure 2: Power spectra of the GRIMM-2 magnetic field calculated at the Earth's reference radius for year 2010. Presented are the spectra of the core field snapshot, its SV and acceleration.

The model inversion process has been regularized by minimizing a measure of the model third temporal derivative. This is compatible with the order six B-spline representation used. In order to improve the robustness of the model near the end of the data time span, the second temporal derivative has been minimized at the model end points. These constraints have been applied at the core-mantle boundary such that the derived model is optimized there. This point is one of the significant differences with the first version of the GRIMM model. With these constraints the GRIMM-2 model presents a relative smooth temporal behavior.

Overall, the data set represents more than 7 millions data values, and the model itself consists of around 6300 parameters. To solve this problem, a code has been developed over several years in a parallel computing environment, nonetheless several days are required to derive a model using the iterative re-weighted least squares approach.

Figure 2 presents the magnetic field energy of the static core field, its SV and acceleration, as a function of the Spherical Harmonic (SH) degree, all calculated at the Earth reference radius (6371.2 km). All present the expected converging spectra. Above SH degree 13, the SV is very small and cannot be resolved. The static

field spectra flatten because of the contribution of the lithospheric field. Although the magnetic field and its SV are not changing too rapidly with time, it has been observed that the acceleration evolved rapidly on annual time scales. This causes significant difficulties for predicting the SV evolution for the coming five years.

Figure 3 present the vertical down component of the core magnetic field, out of the GRIMM-2 model, calculated at the Earth surface for year 2010. In Figure 3 the magnetic equator where the vertical component vanishes is clearly visible. Also visible is the weakness of the field in the Southern part of the Atlantic Ocean and South America. This feature is associated at the core-mantle boundary with a patch of reverse flux. In Figure 4, one can see that the SV is the largest at mid latitudes. The strength of the vertical down component decreases rapidly in the eastern part of the Atlantic Ocean, while it increases in the north of the Indian Ocean. The SV is weak over the Pacific Ocean.

3. IGRF candidates

Three contributions were required for the IGRF candidates:

- 1) a snapshot of the field for year 2005,
- 2) a snapshot of the field for year 2010,

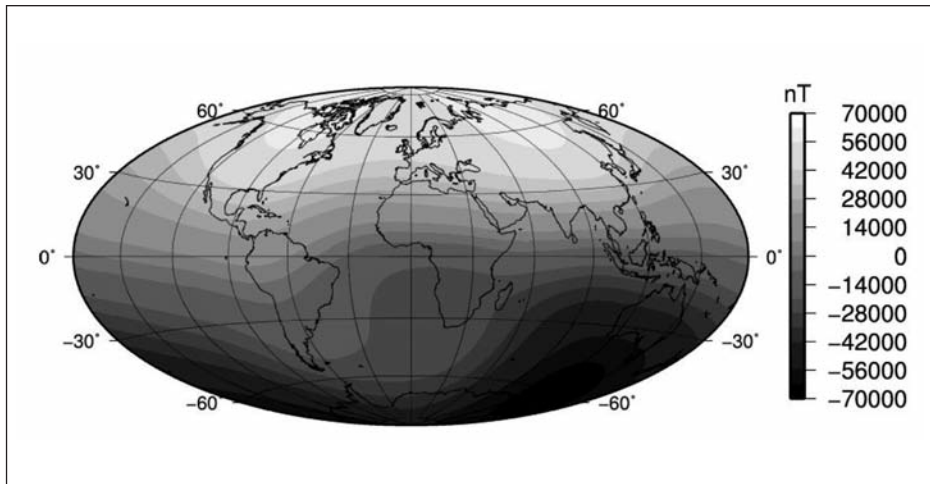


Figure 3: Vertical down component of the main magnetic field estimated using GRIMM-2 model, for the year 2010 and at the Earth's surface.

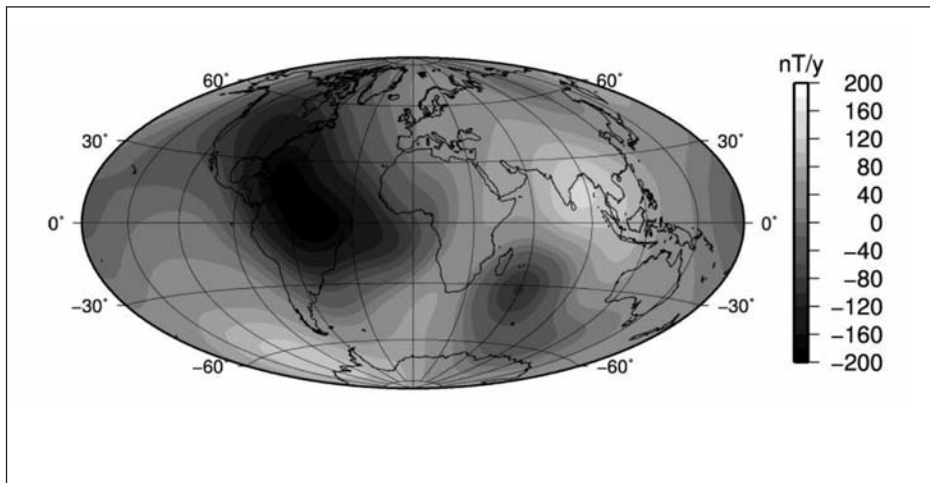


Figure 4: Vertical down component of the main magnetic field secular variation estimated using GRIMM-2 model, for the year 2010 and at the Earth's surface.

3) a predictive SV variation for 2010-2015. Because the data set used in the GRIMM-2 model extend only up to 2009.5, it has been necessary to extrapolate the model in order to derive the 2010 snapshot and the 2010-2015 SV models. A short description is given below.

A candidate for the Definitive Geomagnetic Reference Field (DGRF) model for epoch 2010 has been derived by averaging the GRIMM-2 model between 2004.5 and 2005.5. This was done in order to improve the robustness of the Gauss coefficient estimates. The

resulting model has been truncated to SH degree 13. Compared with the GRIMM-2 model at epoch 2005, the DGRF candidate does not differ by more than 0.25nT for any of the Gauss coefficients. The maximum difference is reached for the coefficient g_1^1 .

A candidate model for the IGRF for epoch 2010 has been derived by extrapolating the GRIMM-2 Gauss coefficients for year 2009 using the SV values at the same epoch – i.e. the acceleration between 2009 and 2010 has been simply ignored. This approach was used because the

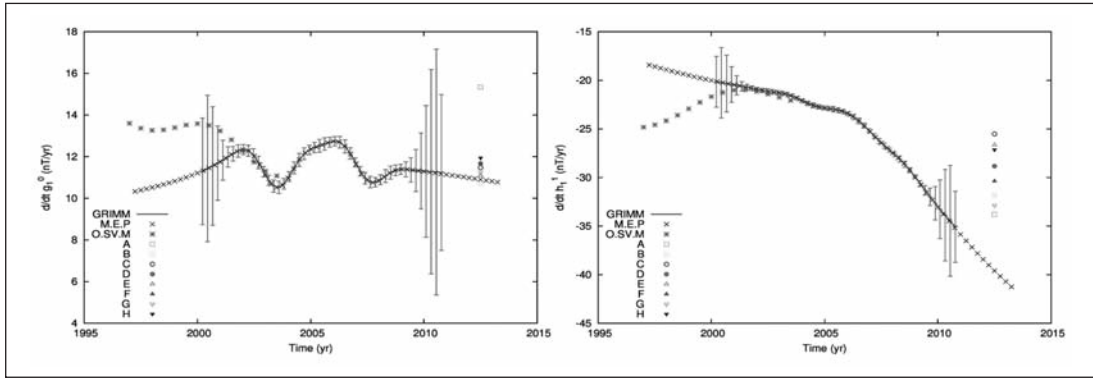


Figure 5: SV coefficients g_1^0 and h_1^1 as estimated by various field models, candidates and extrapolation processes where: GRIMM are the estimated coefficients with error-bars as obtained by the »GRIMM-2« parent model, »M.E.P« are the estimates obtained by applying the maximum entropy method, »O.S.V.M« are the coefficients as obtained from a 50 years field model derived from monthly mean observatory data. The candidate estimates are labeled from »A« to »H«.

GRIMM-2 acceleration model after 2009 is not robust due to the lack of data after 2009.5. Compared with the model directly estimated from GRIMM-2, the IGRF candidate differs by 1.5 nT for the Gauss coefficient h_1^1 . The differences stay below 1nT for any other coefficients.

Regarding the SV predictive model, SV Gauss coefficients variation estimates were derived by linearly interpolating the individual Gauss SV coefficients given by GRIMM-2 over the 2001, 2009.5 periods. These linear interpolations were used to extrapolate the SV coefficients from 2009 to epoch 2012.5.

Figure 5 illustrates the difficulties in predicting the SV over a five-year period. Although the SV is robustly estimated when data are available, the error-bars on GRIMM-2 Gauss coefficients show large uncertainties in these estimates as soon as they are associated with an extrapolation process. The Maximum Entropy Prediction technique (MEP) is often considered as the most reliable extrapolation technique, but when compared with true estimates coming from another model – here the OSVM model (Lowes, 2004) – it is clear from the Figure 5, that the MEP technique may fail. The candidate models, numbered from A to H, differ significantly from each other. Our candidate derived from GRIMM-2 is the G model.

Information about candidate models submitted to DGRF (2005), IGRF (2010) and predictive-SV (2010 to 2015) can be downloaded from the websites:

<http://www.ngdc.noaa.gov/IAGA/vmod/candidatemodels.html>

<http://www.ngdc.noaa.gov/IAGA/vmod/igrf.html>

4. Conclusion

We have briefly presented some of the developments associated with the processing of the CHAMP magnetic vector data. The main progresses have been made in improving the processing of the ASC data. The re-estimation of the Euler Angles using a new independent algorithm shows a good agreement between the different estimates of these angles. The remaining differences are only minor and well inside the expected accuracy of the angles.

We have also presented the second generation of the GFZ Reference Internal Magnetic Model (GRIMM-2). As for the first generation, the model has been derived to provide an accurate description of the core field, its temporal behavior and in particular of the secular acceleration. The GRIMM-2 model has been compared and tested again a direct concurrent – CHAOS-2 (Olsen et al., 2009) — and proves to be robust. The model is accurate over the data

time span, but may not be an accurate representation of the Earth's main field outside this time period. The GRIMM-2 model was used as a parent model to derive the GFZ candidate to the IGRF-11.

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