ADDITIONAL INFORMATION
ABOUT EOST-LPGN-LATMOS-IPGP CANDIDATE MODELS

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1) Internal field (main field) for 2010.0 to degree and order 13

The IGRF-11 model describes the magnetic field of internal origin up to degree and order 13, for epoch 2010.0. We computed this predictive model in two steps. First, we developed an internal field model based on very recent CHAMP satellite magnetic measurements, and second we extrapolate this model to the correct epoch using sub-products of the SV models as described in 2).

Data:

- ✓ *datasets:*
  CHAMP data (both vector and scalar)
- ✓ *period:*
  June and July 2009 (Last period available with both vectorial and scalar data at the time of the data selection)
- ✓ *effective model date:*
  the mean epoch of measurements is 2009.485
- ✓ *selection and rejection criteria :*
  - Field-Aligned Currents effects were minimized, by using only scalar measurements (or vector measurements converted to scalar measurements) above 50° absolute geomagnetic latitude.
  - Day time external fields were reduced by selecting data between 22:00 and 6:00 local time.
  - A selection was done with respect to geomagnetic activity indices. Only data corresponding to the following criteria were kept :
    - ➢ $|Dst(t)| < 5$ nT
    - ➢ $|d\,Dst(t)/dt| < 3$ nT/h
    - ➢ $Kp(t) < 1+$
    - ➢ $Kp(t+/-3h) < 2-$

    The alpha 30 minutes sectoriel indices we used for the DGRF model were not yet available for the considered time period.
  - Data were decimated along track, keeping only one out of ten measurements.
  - Date were also decimated on an equiangular grid of 3°x3°. For each month, up to ten measurements per bin were selected. When a bin was full of data, the data farest from midnight was withdrawn. The global geographical distribution of data was checked: there is at least two measurements in each 4x4° bin over the entire surface (see Figure 1).
- ✓ *weights allocated to the different kinds of data:*
  - Equal weight was given to scalar and vector measurements.
  - A $1/\sin(\Theta)$ weighting scheme was sued to counterbalance the denser data distribution close to the poles.

- ✓ *Summary:*

  The final dataset is made of 66027 scalar measurements and 55111 vector triplets. The mean model time is 2009.485

Modeling:

The initial main-field model based on CHAMP satellite measurements is computed up to degree/order 14 for internal field and 2 for external field, without any secular variation as the time-span of the dataset is about 2 months.

- ✓ *method:*

  We used a least-square approach (Cain et al., 1967; Langlais et al., 2002). The initial model is a model based on MAGSAT measurements, and described in (Langlais et al., 2002). However, the choice of a particular model has no effect as shown by Ultré-Guérard (1996). Convergence was reached after only 3 iterations. We did not use any regularization.

- ✓ *fit to the data:*

  The mean deviation (in a root-mean square sense) is 8,81 nT, distributed as 10.18 nT (scalar measurements), 6.60 nT (X component), 4.05 nT (Y component) and 11.90 nT (Z component).

Extrapolation to epoch 2010.0:

- ✓ *forward extrapolation to 2010.0 for the field coefficients:*

  The model is computed at epoch 2009.485. It is extrapolated up to 2010.0 by applying the secular variation of model VS2009.0 (multiplied by 0.015) and of SV 2010.0 (multiplied by 0.5). Only terms for degree lower or equal to 8 are extrapolated. Terms for higher degrees are not updated.

Estimated accuracy of the coefficients:

Formal errors are very small and not significant. We do not present them. Because the model is extrapolated to epoch 2010.0 (for n<=8), error related to the secular variation is introduced. Terms of higher degree are not extrapolated; the associated error may then be as large as the secular variation. We therefore estimated individual noises for coefficients (Figure 2) using the following scheme:

- ➢ for n <=8, the individual error of Gauss coefficients is taken as the half of the error associated with the IGRF-SV model (as described in part 2)
- ➢ For n>8, the individual error of Gauss coefficients is taken as half of the SV gauss coefficients computed in model_12month as described in the DGRF part of this document.

These errors have to be seen as maximum errors affecting each Gauss coefficients at epoch 2010.0, not as modelling errors.

Our main field candidate model for IGRF-11 (epoch based 2010.0) is a truncated and rounded (to the nearest 0.01nT) version of this model, up to degree/order 13.

FIGURE 1: *Champ data distribution used in the elaboration of the initial main-field model for IGRF 11- MF.*

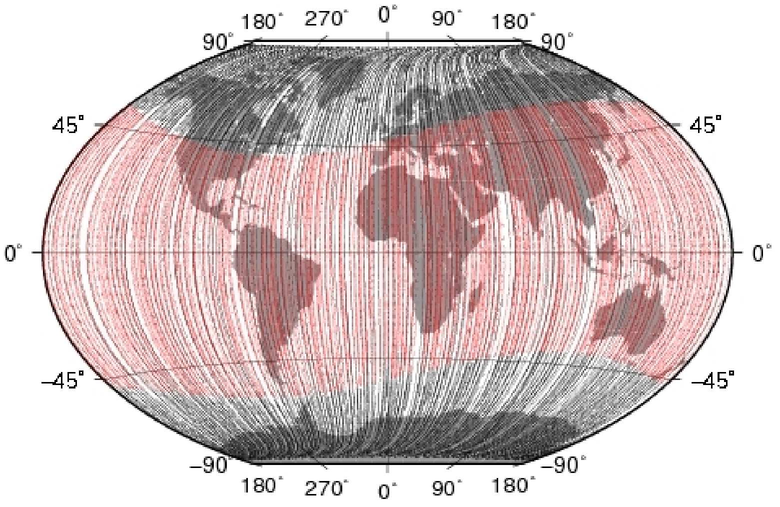
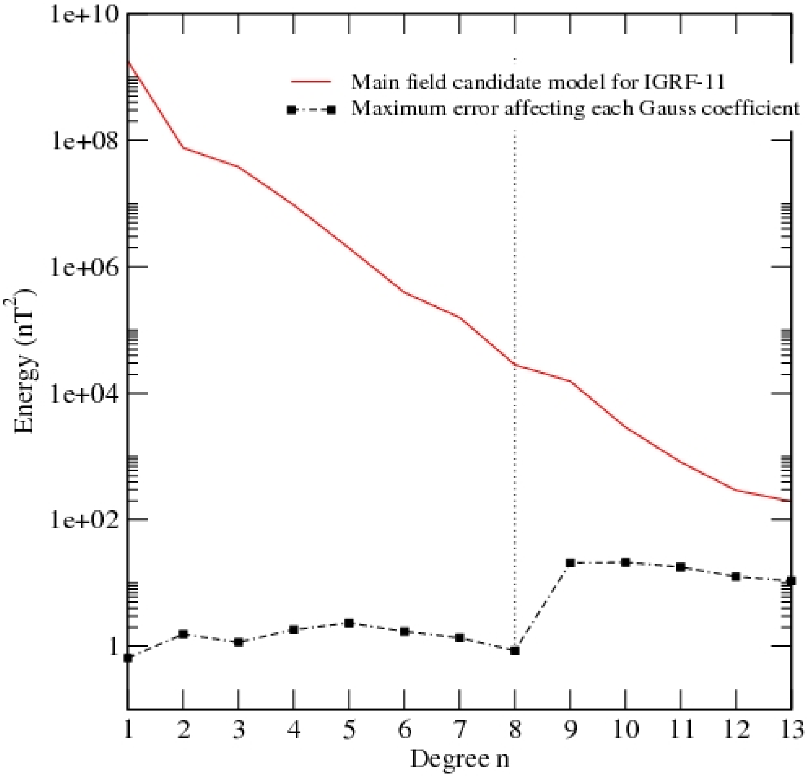


FIGURE 2: *Energy Spectra of the candidate model IGRF 11-MF and the evaluated spectra of errors due to the secular variation introduced (not errors linked to modelling).*



2) Internal field secular variation for epoch 2010.0 to 2015.0

We chose to use time series of observatory annual means to model and predict the secular variation. This approach allows the temporal variations of the magnetic field to be better identified and separated from the geographical variations. The approach is very similar to that used by Langlais and Mandea (2000) when proposing a candidate SV model for IGRF-2000.

Data:

Only observatory data were considered. Hourly mean values were collected from the World Data Center (Edinburgh), and monthly mean values were computed. We disregarded observatories for which time series were shorter than 11 years.

Out of a gross total of 200 observatories providing data between 1980 and 2008, only 96 observatories were retained for this study. Many were rejected because they ceased operations before (or did not provide data after) 2005, some others were rejected because of very long data gaps. Time series were plotted and individually checked to disregard possible outliers; which were removed.

These time series were compared to two other datasets: the IPGP monthly mean value database, and the values computed (until 1998) by Langlais and Mandea (2000). This dual comparison allowed some spurious jumps to be identified and eliminated. The final dataset consists of 96 observatories (list available on request; see the geographical distribution on Figure 3), with monthly means values at least between 1997 and 2007/8 (inclusive).

These 96x3 time series were extrapolated until the end of 2015, using an exponential smoothing scheme with an additive seasonal trend (period 12 month). The best fit was automatically computed, using the Statistica (© Statsoft) software. Missing values were linearly interpolated, the longest gap being 24 month. Times series of true, interpolated and extrapolated data were plotted and individually examined. In some cases where the extrapolation appeared odd, extrapolations were compared to provisional hourly means (obtained from observatories or from INTERMAGNET), to check spurious extrapolated trends. All of them were actually observed.

Annual means were thereafter derived from the monthly means, between 1980.5 and 2015.5. We then computed annual differences at each observatories, from 1981.0 to 2015.0. This allows to limit the influence of otherwise non-accessible features through modelling, such as large crustal biases or regional field.

Modeling:

- *Method*

  Annual differences were used to compute annual models of the secular variation, without taking into account the internal main field. Gauss coefficients up to degree and order 8 were computed, as well as up to degree 1 for the external field. This external field was found to be little, but accounted for the year-to-year variations of the mean external field.

  The same modeling scheme as previously was used, based on a least square approach. Convergence to the final models was reached after only one iteration. The initial model was null, we did not use any regularization.

  Each individual observatory annual means (real data and extrapolated ones) data were weighted accordingly to the inverse of the mean distance of the four closest observatories in the four NW, NE, SE and SW quadrants, as detailed in Langlais and Mandea (2000).

- *Fit to the data*

  Fit to the X, Y and Z components varied from on year to another. Prior to 2008.0 (i.e., for models based on true observations), rms errors ranged between 2.21 and 4.14 nT for X, 2.74 and 4.24 nT for Y, and 1.60 and 3.98 nT for Z. After 2008 (i.e. for models based on data predictions), errors on field component variations are of the order of 3.56 nT, 2.89 nT, and 2.67 nT for X, Y and Z, respectively.

Final model for epoch 2010.0 to 2015.0

Our series of model is made of 35 SV models, from 1981.0 to 2015.0, each one being centered on the the first day of the given year. This long time series allowed us to check the consistency of the predicted secular variation for epoch 2009-2015.

The final model (Figure 4) for epoch 2010.0/2015.0 is the mean of the following models: SV2009 (*1/2), SV2010. SV2011, SV2012, SV2013, SV2014, SV2015(*1/2).

Estimated accuracy of the coefficients:

Formal errors (i.e. based on the rms differences between the candidate model and the 6 models above mentioned) are very small and meaningless. We chose instead to use the rms difference between an SV2005, SV2006, SV2008, SV2009 on one hand, and the mean of these four models, on the other hand. These rms are actually proportional to the observed variations of the secular variation for the past four years.

Our secular variation candidate model for IGRF-11 (over 2010.0-2015.0) is a rounded (to the nearest 0.01nT) version of this model, up to degree/order 8.

FIGURE 3: *The 96 geomagnetic observatories used to calculate the secular variation model.*

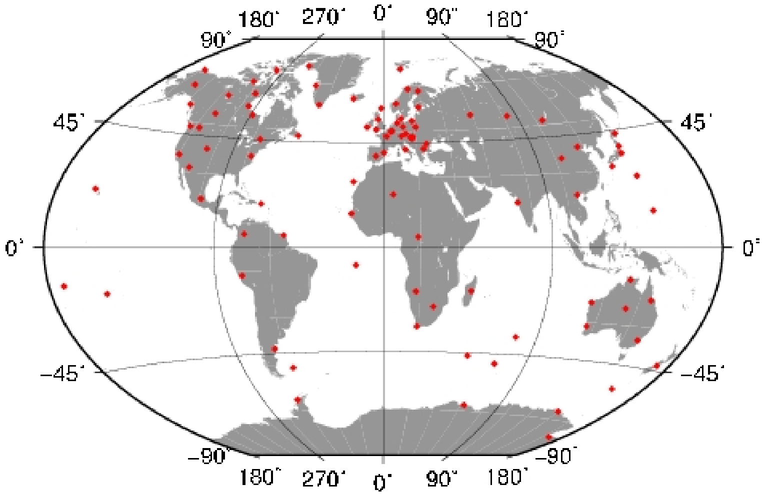
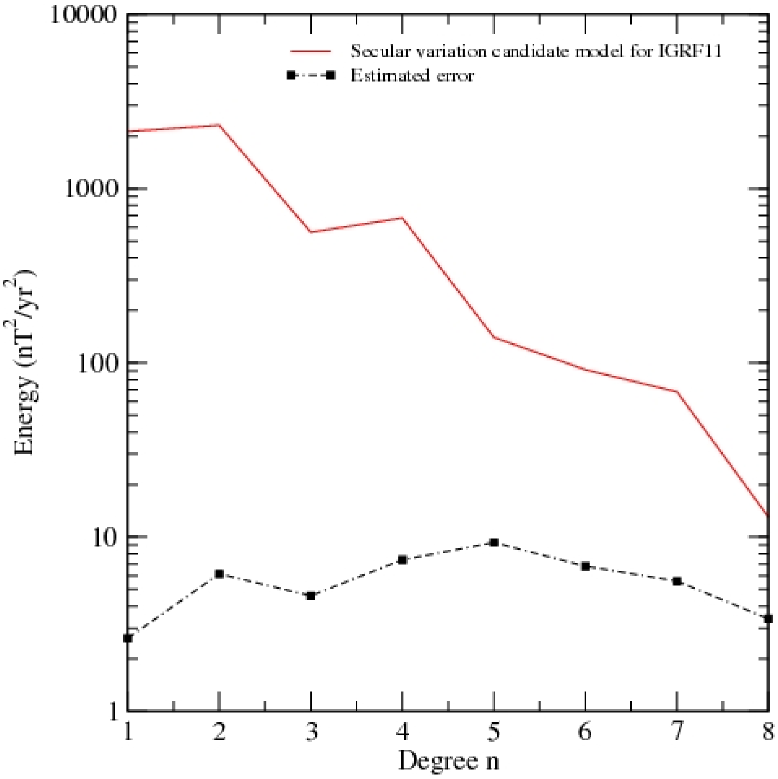


FIGURE 4: *Energy Spectra of the candidate model IGRF 11-SV and the evaluated spectra of errors due to the final computation by means.*



3) Internal field (main field) for 2005.0 to degree and order 13

The DGRF describe what is thought to be more accurate description (within the model limitation) of the magnetic field of internal origin for a given epoch. We chose to use about one year of measurements, centered around 2005.0, taking into account a secular variation part.

- ✓ *Dataset*:
  - data source: CHAMP and Oersted satellite magnetic measurements (both scalar and vector)
  - period: from July 2004 to June 2005.
  - minimization of external fields: as for IGRF-MF, only scalar measurements above 50° absolute geomagnetic latitude were retained. A local time 22:00-06:00 selection was applied. The magnetic sectorial index alpha 30-minutes was used, and only measurements associated with $\alpha_{30''}$ ranging between 0 and 4 nT were kept. A selection was done with respect to Dst geomagnetic activity index. Only data corresponding to the following criteria were kept :
    - $|Dst(t)| < 30$ nT
    - $|d\, Dst(t)/dt| < 10$ nT/h
  - decimation: data were decimated along track, keeping only one out of ten measurements.
  - geographical distribution: a maximum of 1 measurements per 1x1◦ was retained for each month. Whenever possible, those measurements with lower $\alpha_{30''}$ were selected. All cells were filled. The final dataset contains 144004 (CHAMP scalar), 88971 (CHAMP vector triplets), 92790 (Oersted scalar), and 13674 (Oersted vector triplets) measurements. The

distribution of the final dataset was checked (Figure 5): there is at least one measurement in each 3x3° cell.

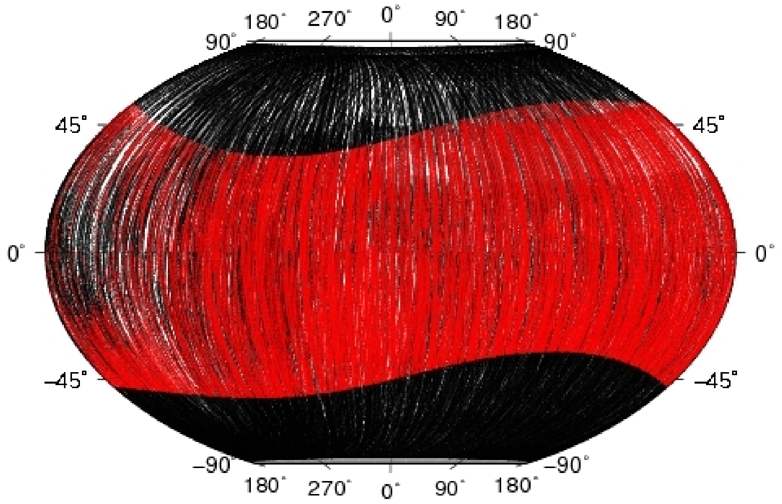
- ✓ *weights allocated to the different kinds of data:*
  Weights were allocated according to the nature of data, following :
  - Champ scalar: $1/\sigma^2$ ($\sigma = 2.00$nT)
  - Champ vector triplets: $1/\sigma^2$ ($\sigma = 2.00$nT)
  - Orsted scalar: $1/\sigma^2$ ($\sigma = 3.00$nT)
  - Orsted vector triplets: $1/\sigma^2$ ($\sigma = 3.00$nT) combined with an anisotropic weighting-scheme based on the attitude uncertainty (Holme, 2000). Error angles were set to 10 arcsec for the direction along the SIM axis, and to 60 arcsec for the perpendicular direction.
  - An additional $1/\sin(\Theta)$ weighting scheme was used to counterbalance the denser data distribution close to the poles.

- ✓ *modeling:*
  - ➢ The main-field model for 2005.0 was computed up to degree/order 15 for internal field, 2 for external field and 1 for Dst dependency, with a secular variation up to degree and order 8.
  - ➢ A least square process was used, convergence was reached after 3 iterations
  - ➢ No regularization was used:
  - ➢ *fit to the data:*
    - Orsted scalar : 4.14 nT
    - Orsted vector : 3,41 nT (B direction) 11,43 nT (perpendicular to B and to the SIM direction), and 6,77 (third complementary direction)
    - CHAMP scalar: 7,87 nT
    - CHAMP vector: 4,87 nT (X), 4,86 nT (Y) and 5,22 nT (Z)

Final model and associated error:

Our candidate model for DGRF 2005.0 is a truncated and rounded (to the nearest 0.01nT) version of this final model, up to degree/order 13. (There is no estimated error of the coefficients.)

FIGURE 5: *Champ and Oersted data distribution used in the elaboration of the main-field model for candidate to DGRF 2005.0:*



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