ADDITIONAL INFORMATION ABOUT BGS CANDIDATE MODEL

General structure of parent model

The British Geological Survey's IGRF-11 candidate is based on a degree and order 60 spherical harmonic expansion of selected vector and scalar magnetic field data from satellite and observatory sources within the period 1999.0 to 2010.0. The parent model's internal field time dependence is by cubic polynomials for degrees 1 to 20. The parent model's degree 1 external field time dependence is by periodic functions for the annual and semi-annual signals, and by dependence on the 20-minute Vector Magnetic Disturbance index. Signals induced by these external fields are also parameterised.

The derivation of the parent model depends to a large extent on the work published in the papers listed below (but are superseded by any additional information given in this document):

Thomson, Alan W. P., Brian Hamilton, Susan Macmillan and Sarah J. Reay, 2009. A Novel Weighting Method for Satellite Magnetic Data and a New Global Magnetic Field Model, *Geophys. J Int.*, submitted.

Thomson, A. W. P., and Lesur, V., 2007. An Improved Geomagnetic Data Selection Algorithm for Global Geomagnetic Field Modelling, *Geophys. J. Int.*, 169, 951-963.

Lesur, Vincent, Susan Macmillan and Alan Thomson, 2005. The BGS magnetic field candidate models for the 10th generation IGRF. *Earth, Planets and Space*, 57, 1157-1164.

Which satellite, observatory and repeat station data sets were used?

CHAMP (calibration level version 51) scalar and vector data between 2000.6 and 2009.6.
Oersted vector data between 1999.2 and 2005.9.
Oersted scalar data between 1999.3 and 2009.4 (mostly from 2005 and onwards).
For both CHAMP and Oersted, scalar data were used only where no vector sample was available.

Observatory data from 152 observatories between 1999.0 and 2009.5, known jumps applied, some poor quality data eliminated manually.

What were the data selection and rejection criteria?

Every 60^{th} satellite data were sampled (~68 sec):

(i) Magnetic indices: K_p and K_p for previous 3 hours ≤ 2-; |dDst/dt| ≤ 5 nT/hour; IE <= 30 nT; PC ≤ 0.2 mV/m;

(ii) Solar wind data: 0 ≤ IMF Bz ≤ +6 nT; -3 ≤ IMF By ≤ +3 nT; -10 ≤ IMF Bx ≤ +10 nT; solar wind speed ≤ 450 km/s;

(iii) Other: 22:30 <= local time (hour:min) <= 05:00, |observed magnetic field value - value from *a priori* model| ≤ 100 nT; |scalar F from OVH – vector F from CSC| ≤ 2 nT

Observatory hourly means:

(i) Magnetic indices: $K_p \leq 2+$, $|dDst/dt| \leq 5$ nT/hour
(ii) Solar wind data: IMF Bz ≥ 0 nT
(iii) Other:night-time (01:00 to 02:00 LT + darkness test at 110 km altitude above observatory)

What weights were allocated to the different kinds of data?

The selected satellite data were individually weighted based on two "noise" estimators. Firstly, a measure of local magnetic activity using the standard deviation along short segments (60 samples) of satellite track. Secondly, a larger-scale noise estimator derived from activity measured at the geographically nearest magnetic observatories to the sample point. These estimators downweight the vector data at high latitudes.

Were data weighted for equal spatial or temporal coverage?

Data were weighted for equal spatial coverage using 1-degree equal-area tesseral weighting. No weighting was applied to achieve equal temporal coverage.

How was the forward extrapolation to 2010.0 for the field coefficients done?

We interpolated the parent model (max degree and order 60, cubic time-dependence up to degree and order 20) to extract a set of coefficients for 2004.0 and 2009.0. The mean secular variation from 2004.0 to 2009.0 up to degree and order 20 was used to extrapolate the 2009.0 coefficients to 2010.0.

How is the average secular variation from 2010.0 to 2015.0 predicted? Was the present secular variation taken, or was it forward extrapolated to 2012.5? Was the procedure tested by hind-casting the known field at earlier times?

The average secular variation from 2010.0 to 2015.0 was assumed to be the same as the average secular variation up to degree and order 8 between models interpolated at 2004.0 and 2009.0. The model was not tested by hindcasting.

If iterating the Least Squares process, what was the starting model used, and how many iterations were needed?

The starting model assumed g1,0 = -10000.0 and all other coefficients were set to 0.0. One iteration was performed using an L2-norm. Three subsequent iterations were performed using an L1-norm.

What, if any, regularization was used, e.g., use of an a-priori model with specified (co-)variance, or addition of some quadratic penalty function to the sum square deviation?

No regularization was used although very small eigenvalues were rejected.

What was the method used to solve the Least Squares equations?

Iterative reweighted least-squares technique.

What was the fit to the data?

In nanoTesla:

Satellite residuals in solar magnetic XYZ directions:
Residual average : 0.71 with standard deviation : 11.66
Residual average : 0.00 with standard deviation : 11.29
Residual average : 1.25 with standard deviation : 9.48

Satellite residuals in geocentric North-East-Down directions:
Residual average : 0.47 with standard deviation : 12.11
Residual average : 0.23 with standard deviation : 11.65
Residual average : -0.50 with standard deviation : 8.52

Satellite F residual:
Residual average : -0.72 with standard deviation : 6.71

Observatory residuals in geocentric North-East-Down directions:
Residual average : -0.90 with standard deviation : 7.74
Residual average : 0.14 with standard deviation : 5.66
Residual average : 0.45 with standard deviation : 7.56

Observatory projected-F residual:
Residual average : -2.09 with standard deviation : 17.51

Please give some indication of the (co-)variances of the resulting set of coefficients. One possibility is to estimate models from different data sub-sets (e.g. CHAMP+Observatory versus Oersted+Observatory) and comparing the resulting models.

No estimate is available.