TEST OF MAIN FIELD AND SECULAR VARIATION CANDIDATE MODELS for IGRF-10 USING OBSERVATORY MONTHLY MEAN VALUES.

Benoit Langlais, Mioara Mandea and Aude Chambodut

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We tested the candidate models for the IGRF-10. We limited the number of models, restraining our tests to the models A1, B3, C1 and D1 for the main field models, and to the models A3, B3, C1, and D1 for the secular variation models. The mean of the four models for the main field is denoted E0. The mean of the four models for the secular variation is denoted E0. A sixth secular variation was introduced, the IGRF-9, denoted F0 in the following.

Our tests are based on observatory monthly mean values for the first 6 months of 2004. We preferred to use this very limited data set instead of a more complete satellite dataset, as none of the candidate models used these values. Another reason is that IGRF users are less likely to use satellite measurements than ground measurements.

We first introduce the used data set. Then we present the tests on the MF candidates, and on the SV candidates. We finally give our recommendations with respect to our tests.

1. Data set

Data were collected from 41 observatories. Two of them provided incomplete time series, and were thus disregarded (IRD and TSU). For another one (QSB) the Z component was missing. We also rejected the measurements of CSY, as the time variability of the measurements was too large (500 nT and more).

The final data set is thus made of 37 observatories, each of them providing monthly mean values of the three X, Y and Z magnetic components from January to June 2004 (37*6*3 measurements). IAGA codes and positions are given in table 1. Figure 1 shows the geographical distribution for the dataset.

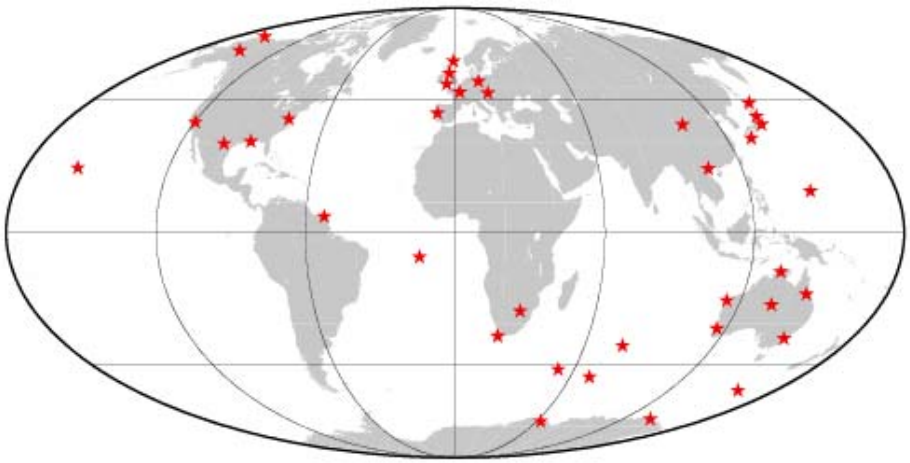

Figure 1- Geographical distribution of the 37 observatories

Crustal anomaly biases were estimated whenever possible. They can be estimated as the difference between observations and model predictions (see Mandea and Langlais, 2002, for a complete description). The magnetic field is predicted up to degree and order 13, thus describing the internal (core) part. In order to get the most precise crustal biases, we chose a main field model that was the least contaminated by the local field. The chosen model is denoted as *oersted_03f_03.cof* (Olsen, 2003). This model is based on Ørsted measurements, from January 2001 to January 2003. It is developed up to degree and order 29 for the main field, 16 for the linear secular variation, and 2 for the external field (static, annual and semi-annual terms). We truncated this model to degree 13 for the main field and the secular variation, and took only the static external field into account.

We collected the annual mean values using the BGS data bases, for the years 2001 and 2002. All but 4 observatories had 2 values: CTA had a 2001 annual mean, while MAW had a 2002 annual mean. For the ASC and LRM observatories, no annual mean values were available. The ASC crustal biases were evaluated by interpolating the 2000 and 2003 annual mean values. The LRM crustal biases were not evaluated.

The field was predicted for 2001.5 and for 2002.5, taking into account the secular variation. Differences were computed, and biases were taken as the mean of the two 2001 and 2002 differences. We compared the newly derived crustal magnetic biases to previously published ones. Differences are small [detailed statistics will be made available later].

Although limited, our dataset almost reflects the actual distribution of magnetic observatories around the world. North America, Europe and Japon are weel covered, as well as the Australian continent. There are few observatories in ocean areas (about 20% of our dataset)

Table 1 - Observatory positions and associated crustal biases

Code	Alt (m)	Lat (°)	Lon (°)	X_{crust} (nT)	Y_{crust}(nT)	Z_{crust} (nT)
ASC	0.177	-7.950	345.617	-506	257	36
AMS	0.048	-37.833	77.567	-579	-661	-1975
ASP	0.557	-23.767	133.883	45	-17	44
BRW	0.000	71.317	203.367	49	-60	-40
BSL	0.000	30.350	270.367	-73	27	56
CLF	0.145	48.017	2.267	-75	-16	97
CMO	0.090	64.867	212.133	11	1	-36
CNB	0.859	-35.317	149.367	-9	44	87
COI	0.099	40.217	351.583	1	-30	-52
CTA	0.370	-20.083	146.267	-451	-88	175
CZT	0.155	-46.433	51.867	-762	1091	174
DLR	0.357	29.483	259.083	116	79	59
DRV	0.030	-66.667	140.017	-146	-413	-2799
ESK	0.245	55.317	356.800	13	-42	-64
FRD	0.069	38.200	282.617	56	-61	119
FRN	0.000	37.083	240.283	-22	-22	-237
GNA	0.060	-31.783	115.950	-14	-105	117
GUA	0.150	13.583	144.867	128	75	55
HAD	0.095	51.000	355.517	-40	11	61
HBK	1.522	-25.883	27.700	99	-14	57
HER	0.026	-34.417	19.233	18	11	39
HON	0.003	21.317	202.000	-164	86	-323
KAK	0.028	36.233	140.183	-1	7	-107
KDU	0.014	-12.683	132.467	6	-32	33
KNY	0.105	31.417	130.883	-6	51	-40
KOU	0.010	5.300	307.267	105	97	-132
LER	0.085	60.133	358.817	-120	159	30
LRM	0.004	-22.217	114.100	0	0	0
LZH	1.560	36.083	103.850	2	0	-91
MAW	0.012	-67.600	62.883	27	12	195
MCQ	0.008	-54.500	158.950	263	3	291
MIZ	0.125	39.117	141.200	-62	41	-299
MMB	0.039	43.917	144.200	-220	142	40
NCK	0.160	47.633	16.717	-21	5	-66
NGK	0.078	52.067	12.683	-26	2	-89
PAF	0.015	-49.350	70.250	437	-142	-305
PHU	0.005	21.033	105.95	7	12	-25

2. Main field models testing

The field measured at a given epoch can be described as

$$B_{obs}(T) = B_{mod}(T0) + B_{crust} + B_{ext,static} + B_{ext,\ non\ static}(T) + B_{SV}(T\text{-}T0) + B_{error}$$

B_{crust} corresponds to the crustal term. B_{mod} is the field predicted by the candidate model, at epoch T_0 = 2005.0. $B_{SV}(T\text{-}T_0)$ can be estimated from the IGRF-9 SV model, or neglected. We will see in the following that this doesn't affect the results. $B_{ext,static}$ is the external static field. In the following, it is estimated from external Gauss coefficients up to n, m = 2. The last term $B_{ext,\ non\ static}(T)$ is not evaluated. But we can expect this term to be relatively small.

We present in the tables 2 to 6 the values of the room mean square differences, taken as:

$$\sigma = \{\sum[B_{obs}(T)-B_{mod}(T_0)]^2 /N\}^{1/2}$$

Only total field residuals are presented. Field components showed similar behaviors, X and Y being slightly lower than B, while Z was larger.

Table 2 - rms differences (total field) between observations and model predictions. No external field, no secular variation, no crustal correction. Values in nT.

	A1,B	B3,B	C1,B	D1,B	E0,B
JAN	387.2	387.1	386.1	387.2	386.9
FEB	387.0	386.9	385.8	387.0	386.7
MAR	387.3	387.1	386.1	387.3	387.0
APR	387.4	387.3	386.3	387.4	387.1
MAY	386.8	386.7	385.6	386.8	386.5
JUN	386.4	386.3	385.2	386.3	386.1
ALL	385.6	385.4	384.4	385.5	385.2

Table 3 - rms differences (total field) between observations and model predictions. No external field, no secular variation, with crustal correction. Values in nT.

	A1,B	B3,B	C1,B	D1,B	E0,B
JAN	47.5	47.3	49.1	48.5	47.8
FEB	42.8	42.6	44.3	43.9	43.1
MAR	39.7	39.5	41.3	40.9	40.0
APR	38.2	38.2	39.6	39.3	38.5
MAY	34.8	34.7	36.1	35.9	35.0
JUN	32.1	32.0	33.5	33.2	32.3
ALL	39.4	39.2	40.8	40.4	39.6

Table 4 - rms differences (total field) between observations and model predictions. With static external field, no secular variation, with crustal correction. Values in nT.

	A1,B	B3,B	C1,B	D1,B	E0,B
JAN	44.1	43.7	45.7	45.0	44.3
FEB	40.6	40.0	41.9	41.5	40.6
MAR	37.4	36.8	38.8	38.3	37.4
APR	36.2	35.8	37.4	37.0	36.2
MAY	34.4	33.9	35.5	35.2	34.4
JUN	32.5	32.1	33.6	33.2	32.5
ALL	37.6	37.1	38.9	38.4	37.6

Table 5 - rms differences (total field) between observations and model predictions. With static external field, with IGRF-09 secular variation, with crustal correction. Values in nT.

	A1,B	B3,B	C1,B	D1,B	E0,B
JAN	21.4	22.0	24.3	23.0	22.1
FEB	19.4	19.7	21.9	20.9	19.8
MAR	19.7	20.0	22.1	21.2	20.1
APR	22.0	22.4	23.8	23.2	22.3
MAY	22.7	22.8	24.2	23.7	22.8
JUN	23.3	23.4	24.7	24.2	23.4
ALL	21.4	21.7	23.4	22.6	21.7

Table 6 - rms differences (total field) between observations and model predictions. no external field, with IGRF-09 secular variation, no crustal correction. Values in nT.

	A1,B	B3,B	C1,B	D1,B	E0,B
JAN	388.2	388.1	387.0	388.2	387.9
FEB	388.0	387.9	386.8	387.9	387.7
MAR	388.3	388.3	387.2	388.3	388.0
APR	388.5	388.4	387.3	388.5	388.2
MAY	387.8	387.7	386.6	387.8	387.5
JUN	387.4	387.3	386.1	387.3	387.0
ALL	386.6	386.5	385.4	386.5	386.3

Table 2 shows the rms associated with the main field only predictions, Then, First, only the main field was predicted (table 1). Then, we successively took into account the crustal biases (table 3), the static external field (table 4), and the secular variation, taken from IGRF-9 (table 5). Residuals typically decreased from 385 nT to 40 nT, then to 38 nT and to 22 nT. These results clearly show that the main source of error is the crustal field. There is a clear time dependence in tables 3 and 4: residuals are larger in January than in June, which is coherent with what was expected. This dependence disappears in table 4.

From Table 5 we observe that model A1 offers the better fit, closely followed by model B1 (+0.3 nT), model D3 (+1.0 nT) and model C1 (+2.2 nT). The residuals associated with the mean model E0 are lower than the mean of the residuals (21.7 nT vs. 22.3 nT).

However, IGRF users would most likely face the table 6 case: no information on the external field or on the local crustal field. In this case model C1 offers the best fit, but the relative differences between the models are small (≈ 1 nT) with respect to the absolute rms values (≈ 385 nT).

3. Secular variation models testing

Testing the secular variation candidate models is more difficult, as the candidate models are predictive, and valid from epoch 2005.0 until 2010.0 (this is assuming that the field variations can be linearly approximated during 5 years). We thus can not test the models directly. Instead, we assumed that the secular variation is continuous before and after 2005, and that the error due to the extrapolation of the 2005-2010 models back to 2004.0 is relatively small.

It is assumed that the main field model is the MF E0 model previously described, which corresponds to the mean of the 4 MF models. Root mean square values between observations and predictions are given in tables 7 and 8. Only two cases are presented, a realistic one (no external field, no crustal field – table 7), and an ideal one (with a priori information on crustal field and external field – table 8).

From these two tables, we observe that the best fit is associated with model D1. This is certainly due to the model validity date. Model D1 is given for epoch 2005.0. The three other models were given for 2007.5 and give comparable results. Our assumption about the continuity of the secular variation is valid: rms associated with models E0 and F0 are almost identical.

Table 7 - rms differences (total field) between observations and model predictions. no external field, no crustal correction. Values in nT.

	A3,B	B3,B	C1,B	D3,B	E0,B	F0,B
JAN	387.7	386.8	387.2	387.8	387.3	387.9
FEB	387.4	386.6	387.0	387.5	387.1	387.7
MAR	387.8	387.1	387.5	387.9	387.5	388.0
APR	388.0	387.3	387.7	388.1	387.7	388.2
MAY	387.3	386.7	387.0	387.4	387.1	387.5
JUN	386.9	386.4	386.6	387.0	386.7	387.0
ALL	386.1	385.4	385.7	386.2	385.8	386.3

Table 8 - rms differences (total field) between observations and model predictions. with static external field, with crustal correction. Values in nT.

	A3,B	B3,B	C1,B	D3,B	E0,B	F0,B
JAN	23.1	24.2	23.1	21.3	22.2	22.1
FEB	21.0	21.9	20.8	19.3	20.1	19.8
MAR	20.8	21.7	20.6	19.5	20.1	20.1
APR	22.7	23.5	22.4	21.8	22.2	22.3
MAY	23.2	23.7	22.7	22.5	22.7	22.8
JUN	23.7	24.1	23.1	23.1	23.3	23.4
ALL	22.4	23.1	22.0	21.2	21.7	21.7

4. Conclusions and Recommendations

We tested the candidate models for IGRF-10 using an independent approach and dataset. Our dataset was made of observatory monthly mean values for the first 6 months of 2004, which did not enter in any of the IGRF-10 candidate models.

Our tests showed that the main source of error is clearly related to the local (un-modeled) crustal field. When it is taken into account, the rms residuals are almost similar whatever the used main field model. Errors between observations and model MF-E0 are very large when compared to errors between MF model predictions. We therefore recommend that the IGRF-10 MF model is equal to the un-weighted sum of the four A1, B3, C1 and D1 candidate models.

Our tests did not allow the secular variation candidate models to be discriminated. These models are predictive, and any evaluation based on measurements acquired at epochs that does not fall during the validity period is thus speculative. However we observed that the mean model fits the measurements with an equal quality than the IGRF-9 SV model. We therefore recommend that the IGRF-10 MF model is equal to the un-weighted sum of the four A3, B3, C1 and D1 candidate models.

5. Other remarks

5.1 The model we used to estimate the crustal corrections was developed by a member of the group proposing the A-class candidate models. One could argue that such crustal biases would favor the A models. These models do not appear better than the other ones, and thus are not favored because of these crustal biases.

5.2 The MF tests clearly demonstrated than the main source of errors when using IGRF models is the crustal local field, which is un-modeled when considering terms of low degree. Although there is a clear scientific interest in sophisticated magnetic field models, taking into account more magnetic sources, the improvements brought by the use of complex parent models, that are then truncated, appear to be small.

5.3 The SV tests are inconclusive. All models offer similar fits. Candidate models are predictive, and should be valid for the entire 2005-2010 epoch. It would be preferable to produce such models, instead of models extrapolated to a given epoch, 2005.0 (for the D1) or 2007.5 (A3, B3, and C1 models). One could for example think about the mean of five extrapolated models up to 2005.5, 2006.5, 2007.5, 2008.5 and 2009.5. Such a mean model would differ from a 2007.5 model, especially if the extrapolation is taken quadratic.

5.4 In Tatjana Zvereva's email to Susan Macmillan, she mentions two SV models, D1 and D2, the first one being based on satellite data, and the second one based on observatory data. On IAGAV-Vmod web page, there is only a D1 model. We are not sure of the model that we tested (is there an updated version of the D1/D2 model? Or did Izmiran group choose to present only one candidate model?).

5.5 For IGRF1995, Cohen et al. (1997) performed a similar study, testing IGRF candidate models using observatory monthly mean values. The method was quite different, as it took place after 2005.0. As a consequence, more observatory data were available. Rms differences between candidate models and observatory measurements (corrected of the crustal biases) are of the order of 50 nT (when considering the 35 "best" observatories), and near 130 nT when considering the full 67 observatories (see figure 6). IGRF models were developed up to n, m = 10 only. The improvements brought by the n, m = 13 expansion would be then responsible for the 30 nT improvement we observe.

5.6 In table 6, it is interesting to note that the best fit (although the relative differences are small) is associated with the model C1. This model is actually the only one including observatory measurements.

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