

An IGRF candidate main geomagnetic field model for epoch 2000 and a secular variation model for 2000–2005

Benoit Langlais and Mioara Mandea

Institut de Physique du Globe de Paris, B.P. 89, 4 Place Jussieu, 75252 Paris cedex 5, France

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A candidate main geomagnetic field model for epoch 2000, and a secular variation model for the period 2000–2005, are proposed. The main field model is to degree and order 10, the secular variation one to degree and order 8. These models are derived using the method of least squares. A 1997.5 main field model was derived from annual mean values provided by geomagnetic observatories for the 1997.5 epoch, repeat station measurements made in 1997 and reduced to 1997.5, and scalar data since 1995 adjusted to 1997.5. A weighting scheme based on both geographical distribution and data quality was applied. This model was then extrapolated to the 2000.0 epoch, using previously derived secular variation models. To derive these secular variation models, twenty six main field models were firstly computed for epochs 1975.5 through 2000.5, using annual mean values of the X , Y , Z components of the magnetic field from observatories, with the same geographical distribution every year. When missing, annual mean values for 1998, 1999 and 2000 were estimated from extrapolated monthly means, using exponential smoothing and taking account of the seasonal variation. From these twenty six models, twenty five annual secular variation models were extracted, by taking the differences between consecutive main field models. Finally, to produce the IGRF candidate secular variation model, each Gauss coefficient of this set of secular variation models was extrapolated to give values for each year to 2005, using exponential smoothing. So, a mean secular variation model was obtained for the period 2000–2005 and this is proposed for adoption.

1. Introduction

The temporal variation of the geomagnetic field covers a large range of time-scales, from seconds to millennia. Accurate models of the geomagnetic main field and its secular variation are very important for the evaluation of the temporal changes (with time constants of order of a year to a century), but also for many other studies, such as the physics of the Earth's deep interior, global or regional mapping.

To derive good models, data well distributed all over the globe and over long periods of time are essential. The best geographical distribution is provided by satellite data. Unfortunately, up to now there have been few satellite missions dedicated to measuring the geomagnetic field, and only two vectorial satellites. After the launch of the MAGSAT satellite (1979), twenty years have passed until the launch of the new vectorial satellite, Ørsted (February, 23rd 1999)—over this time-span the only other important satellite mission was POGS, which measured only total field intensity with poor accuracy in 1993–1994.

Modelling the main field and its secular variation over long periods of time depends greatly on the network of geomagnetic observatories, which record continuously three components of the field. The present-day network is far from an ideal one, and it needs to be extended and improved, even if in the future satellites measure the field continuously.

It is common to present the internal magnetic field of the Earth in terms of a potential function $V_i(r, \theta, \phi)$, which can

be expressed as a spherical harmonic expansion:

$$V_i(r, \theta, \phi) = a \sum_{n=1}^N \sum_{m=0}^n \left(\frac{a}{r}\right)^{n+1} (g_n^m \cos m\phi + h_n^m \sin m\phi) P_n^m(\cos \theta) \quad (1)$$

where a (6371.2 km) is the mean radius of the Earth, r denotes the radial distance from the center of the Earth, θ and ϕ denote the geocentric colatitude and longitude of a given point. $P_n^m(\cos \theta)$ denote the Schmidt-normalized associated Legendre functions of degree n and order m , and g_n^m and h_n^m denote the Gauss coefficients. Their temporal dependence is:

$$g_n^m(t) = g_n^m(T_0) + \dot{g}_n^m(t - T_0) \quad (2)$$

$$h_n^m(t) = h_n^m(T_0) + \dot{h}_n^m(t - T_0), \quad (3)$$

where \dot{g}_n^m and \dot{h}_n^m represent the Gauss coefficients for the secular variation, i.e., the first temporal derivative of g_n^m and h_n^m , T_0 denotes the epoch of the main field model, and t is the required epoch ($T_0 \leq t \leq T_0 + 5$).

It is now generally agreed that, near the Earth's surface, the magnetic field from the core dominates for the degrees 1–12 and that the magnetic field from the lithosphere dominates for degrees above 14.

In our attempt to produce a candidate main field model for 2000 and a secular variation one for 2000–2005 we chose to concentrate as much as possible on observations made after 1995, the epoch for which the last IGRF model was derived. Unfortunately, at the time of computation, no Ørsted satellite

Table 1. Observatories considered in the MF and SV modelling.

Code ^a	λ^b	φ^c	Date ^d	X_{cc} (nT) ^e	Y_{cc} (nT) ^f	Z_{cc} (nT) ^g	Time period ^h
AAA	43.250	76.916	1980.0	158	14	-8	1980.00-1998.83
AAE	9.000	38.800	1980.0	554	-122	636	*
ABG	18.633	72.867	1980.0	-35	476	659	1980.00-1997.92
ABK	68.360	18.820	1980.0	-10	69	34	*
AIA	-65.250	295.733	1980.0	77	-123	479	1980.00-1988.75
ALE	82.500	297.650	1980.0	-29	73	-102	1984.00-1997.92
AMS	-37.833	77.574	1982.5	-643	-413	-2341	*
API	-13.800	188.233	1980.0	-54	199	-914	1980.00-1997.92
AQU	42.383	13.317	1980.0	-18	45	36	1980.00-1997.92
ARS	56.433	58.566	1980.0	77	-196	528	1980.00-1998.92
ASC	-7.950	345.617	1993.5	...	...	...	*
ASP	-23.767	133.883	1993.5	...	...	...	*
BDV	49.080	14.020	1980.0	-52	-13	2	1980.00-1998.67
BEL	51.833	20.792	1980.0	106	125	336	1980.00-1998.92
BFE	55.633	11.666	1980.0	50	-79	-159	1980.00-1998.42
BJI	40.033	116.183	1980.0	586	-211	455	1980.00-1997.92
BLC	64.317	263.983	1980.0	115	-41	-112	1980.00-1997.92
BNG	4.433	18.566	1980.0	-187	-36	290	1980.00-1998.58
BOU	40.140	254.766	1980.0	-30	15	-137	1980.00-1997.92
BOX	58.033	38.966	1980.0	-22	-46	-405	*
BRW	71.323	203.380	1980.0	-14	-78	-3	1980.00-1997.92
BSL	30.400	270.600	1987.5	...	...	...	*
CBB	69.117	254.967	1980.0	44	-105	28	1980.00-1997.92
CBI	27.100	142.183	1980.0	-328	-27	218	*
CCS	77.717	104.283	1980.0	-76	-103	-57	*
CHD	31.000	103.700	1982.5	-13	71	-114	*
CLF	48.016	2.266	1980.0	-89	2	132	1980.00-1998.92
CMO	64.870	213.856	1980.0	10	-62	23	1980.00-1997.92
CNB	-35.317	149.367	1980.0	30	46	117	1980.00-1998.83
CNH	43.827	125.299	1980.0	-129	33	192	1980.00-1997.92
COI	40.216	351.583	1980.0	37	-19	8	1980.00-1998.83
CRP	10.433	275.083	1979.9	-218	-105	-514	*
CSY	-66.283	110.533	1980.0	844	-264	-842	*
CTA	-20.083	146.250	1984.5	-585	-107	141	*
CZT	-46.433	51.866	1980.0	-792	833	-111	1980.00-1997.92
DIK	73.543	80.562	1980.0	-279	-197	-144	*
DLR	29.490	259.083	1983.5	88	23	86	*
DOB	62.066	9.116	1980.0	-106	-54	-232	1980.00-1998.50
DOU	50.100	4.066	1980.0	-3	80	118	1980.00-1998.92
DRV	-66.666	140.016	1980.0	-136	-394	-2827	1980.00-1997.92
EBR	40.816	0.500	1980.0	41	21	-32	*
ESK	55.316	356.800	1980.0	-15	-27	-59	1980.00-1998.92
ETT	9.167	78.017	1980.5	98	-45	95	*
EYR	-43.416	172.350	1980.0	-26	-27	39	1980.00-1998.92
FCC	58.767	265.917	1980.0	-155	30	-248	1980.00-1997.92
FRD	38.210	282.633	1980.0	34	-79	105	1980.00-1997.92
FRN	37.090	240.280	1983.5	-51	-67	-110	*

Table 1. (continued).

Code ^a	λ^b	φ^c	Date ^d	X_{cc} (nT) ^e	Y_{cc} (nT) ^f	Z_{cc} (nT) ^g	Time period ^h
FUQ	5.467	286.267	1980.0	81	-83	50	1980.00-1997.50
FUR	48.166	11.283	1980.0	-31	0	45	1980.00-1998.92
GDH	69.252	306.467	1980.0	291	-298	771	1980.00-1998.43
GLN	49.650	262.883	1982.5	...	...	...	*
GNA	-31.783	115.950	1980.0	-35	-143	103	1980.00-1998.83
GUA	13.560	144.870	1980.0	84	110	131	1980.00-1997.92
GVN	-70.667	351.733	1994.5	...	...	...	*
GZH	23.100	113.350	1980.0	52	96	33	1980.00-1997.92
HAD	51.000	355.516	1980.0	-64	24	88	1980.00-1998.92
HBK	-25.883	27.700	1980.0	27	27	32	1980.00-1998.75
HER	-34.416	19.233	1980.0	-29	33	-6	1980.00-1998.83
HIS	80.617	58.050	1980.0	86	-675	1121	*
HLP	54.600	18.817	1980.0	37	-162	-50	1980.00-1997.92
HON	21.316	202.000	1980.0	-189	64	-312	1980.00-1997.92
HRB	47.867	18.183	1980.0	-5	-34	-20	1980.00-1998.92
HTY	33.066	139.833	1981.5	-34	-794	458	*
HYB	17.417	78.550	1980.0	339	61	458	*
IQA	63.750	291.483	1995.5	...	...	...	*
IRT	52.166	104.450	1980.0	48	5	-72	1980.00-1998.75
ISK	41.067	29.067	1980.0	129	90	-103	1980.00-1997.92
KAK	36.233	140.183	1980.0	-9	19	-98	1980.00-1998.75
KIV	50.716	30.300	1980.0	3	66	112	1980.00-1998.33
KNY	31.416	130.883	1980.0	-22	28	-33	1980.00-1997.92
KOU	5.217	307.267	1996.5	...	...	...	*
KRC	24.950	67.133	1985.5	...	...	...	*
KSH	39.500	76.000	1987.5	...	...	...	*
LAS	-35.007	302.310	1980.0	-8	1	33	1980.00-1997.17
LER	60.133	358.816	1980.0	-136	197	16	1980.00-1998.92
LNN	59.950	30.700	1980.0	72	31	-235	*
LNP	25.000	121.166	1980.0	3	-16	133	*
LOV	59.350	17.833	1980.0	26	14	33	*
LRV	64.183	338.300	1980.0	-256	594	-503	1980.00-1997.92
LVV	49.900	23.750	1980.0	152	103	165	1980.00-1997.92
LZH	36.083	103.850	1980.0	-18	9	-84	1980.00-1997.92
MAB	50.300	5.683	1991.0	...	...	...	*
MAW	-67.600	62.883	1980.0	-95	25	-21	1980.00-1998.25
MBC	76.317	240.633	1980.0	34	10	-121	1980.00-1997.42
MBO	14.390	343.040	1980.0	80	47	160	1980.00-1998.92
MCQ	-54.500	158.950	1980.0	240	20	289	1980.00-1998.25
MEA	54.617	246.650	1980.0	69	-4	-100	1980.00-1997.92
MIR	-66.550	93.016	1980.0	68	380	-197	*
MIZ	39.117	141.200	1980.0	-88	52	-269	1980.00-1998.83
MMB	43.916	144.200	1980.0	-253	149	72	1980.00-1997.92
MOL	-67.666	45.850	1980.0	-84	-223	-415	*
MOS	55.466	37.316	1980.0	156	-6	219	1980.00-1998.92
MZL	49.600	117.400	1984.5	-134	39	-430	*
NAQ	61.160	314.560	1980.0	-273	254	464	1983.00-1998.42

Table 1. (continued).

Code ^a	λ^b	φ^c	Date ^d	X_{cc} (nT) ^e	Y_{cc} (nT) ^f	Z_{cc} (nT) ^g	Time period ^h
NCK	47.633	16.716	1980.0	-14	-12	-21	1980.00-1998.92
NEW	48.266	242.883	1980.0	-70	91	-47	1980.00-1997.92
NGK	52.066	12.683	1980.0	-49	10	-41	1980.00-1998.83
NUR	60.516	24.650	1980.0	270	-95	136	1980.00-1998.75
NVS	55.033	82.900	1980.0	151	-134	94	1980.00-1998.92
ODE	46.783	30.883	1980.0	-101	-735	21	1980.00-1998.33
OTT	45.400	284.450	1980.0	122	-169	122	1980.00-1997.92
OUL	64.516	27.233	1993.5	...	...	...	*
PAF	-49.350	70.200	1980.0	303	-26	-736	1980.00-1997.92
PBQ	55.283	282.250	1980.0	127	360	34	1980.00-1997.92
PHU	21.033	105.967	1996.5	...	...	...	*
PPT	-17.567	210.417	1980.0	-729	-972	106	1980.00-1997.92
PST	-51.700	302.117	1994.5	...	...	...	*
PTY	-17.250	292.050	1990.5	...	...	...	*
QUE	30.183	66.950	1980.0	62	89	-8	*
RES	74.683	265.100	1980.0	54	49	28	1980.00-1997.92
SBA	-77.850	166.783	1980.0	-2227	-929	-3766	1980.00-1998.92
SFS	36.492	353.882	1991.5	...	...	...	*
SIT	57.066	224.683	1980.0	-19	5	-39	1980.00-1997.92
SJG	18.116	293.850	1980.0	-47	194	189	1980.00-1997.92
SOD	67.366	26.633	1980.0	-188	-97	-582	1980.00-1997.92
SPT	39.550	355.650	1981.5	24	30	-54	1980.00-1998.92
SSH	31.100	121.183	1980.0	-267	71	264	1980.00-1997.92
STJ	47.600	303.317	1980.0	15	48	-15	1980.00-1997.92
SUA	44.683	26.250	1980.0	-2	-67	-77	1980.00-1998.92
SYO	-69.000	39.583	1980.0	-86	-159	-77	*
SZT	28.317	343.567	1980.0	-3103	-829	-490	*
TAM	22.800	5.533	1980.0	24	-232	-39	*
TAN	-18.916	47.552	1980.0	366	-154	-278	*
TEO	19.750	260.816	1980.0	-25	-95	-39	1980.00-1998.92
TFS	42.083	44.700	1980.0	-269	51	-134	1980.00-1998.75
THJ	24.000	102.700	1985.5	...	...	...	*
THL	77.470	290.770	1980.0	-55	148	23	1980.00-1998.42
THY	46.900	17.900	1980.0	-33	-3	-33	1980.00-1997.92
TIK	71.583	129.000	1980.0	-93	-194	-93	*
TNG	-6.166	106.633	1980.0	-1	5	70	*
TRD	8.483	76.950	1980.0	309	247	182	1980.00-1997.92
TRW	-43.267	294.617	1980.0	20	22	14	1980.00-1998.92
TSU	-19.200	17.583	1980.0	60	-110	30	1980.00-1998.92
TTG	3.516	98.566	1982.5	13	59	-77	*
TUC	32.250	249.170	1980.0	-112	-325	440	1980.00-1997.92
VAL	51.930	349.750	1980.0	75	-42	-7	1980.00-1998.92
VIC	48.517	236.583	1980.0	-22	-8	-195	1980.00-1997.92
VLA	43.683	132.166	1980.0	-22	-20	-53	*
VOS	-78.450	106.866	1980.0	-14	153	-4	*
VSS	-22.400	316.350	1980.0	60	-96	-14	*
WHN	30.533	114.566	1980.0	34	66	-34	1980.00-1997.92

Table 1. (continued).

Code ^a	λ^b	φ^c	Date ^d	X_{cc} (nT) ^e	Y_{cc} (nT) ^f	Z_{cc} (nT) ^g	Time period ^h
WMQ	43.816	87.700	1980.0	-42	-98	146	*
WNG	53.750	9.066	1980.0	32	67	-47	1980.00–1997.92
YAK	62.017	129.717	1980.0	69	-1245	124	1980.00–1997.92
YKC	62.483	245.517	1980.0	-47	-49	-184	1980.00–1997.92

^aAccording to the IAGA convention.

^bLatitude of the observatory, in degrees.

^cLongitude of the observatory, in degrees, positive eastward.

^dClose on date to 1980, used to estimate the crustal correction.

^eCrustal contribution in X component, in nT (geographic coordinates).

^fCrustal contribution in Y component, in nT (geographic coordinates).

^gCrustal contribution in Z component, in nT (geographic coordinates).

^hPeriod over which monthly mean values were available (for SV modelling).

data were available. In the following we do not introduce an *a priori* model in our inversion procedure and we do not consider data already used in IGRF1995, such as POGS data or Project MAGNET data.

2. Data

Modelling of the main field and its secular variation is generally based on different sources of magnetic data. In the following we discuss two databases, one for the main field modelling, the other for the secular variation modelling. Also, we describe the applied interpolations and extrapolations.

2.1 Data selection for main field modelling

When deriving spherical harmonic models in the absence of MAGSAT-quality satellite data, it is important to collect data well distributed all over the globe and of good quality. Such models are therefore dependent on geomagnetic observatory data and data from repeat stations. Ship-borne magnetic survey measurements in areas without observatories were also used.

In our attempt to build a main field model for 2000.0 some data selection criteria were adopted. First, we decided to use only the magnetic data which were not included in modelling the main field for 1995 epoch (this gives us the possibility to compute a model which is independent of the IGRF1995). Then, we tried to obtain as many magnetic data as possible for the 1997.5 epoch. This epoch is the middle of the time-span between the two epochs for which IGRF models have to be available. It is also the last epoch for which secular variation models derived from observations rather than predictions can be computed—see Subsection 2.2.

2.1.1 Observatory data The present geographical distribution of observatories is still unbalanced between the Northern and the Southern hemispheres, and obviously between the continental and oceanic regions. Further deterioration is occurring because some observatories are closing, due to economic or political reasons. Also, obtaining the data for recent years is sometimes difficult, because some observatories have a long delay in computing and publishing their data. For the purpose of modelling, three field components were selected: northward (X), eastward (Y) and vertically

downward (Z). The list of available observatories with corresponding IAGA code and geographical coordinates is given in Table 1. The geographical distribution of these observatories is shown in Fig. 1. It is also to be noted that by using annual mean values the external field effects (diurnal variations, seasonal variations and magnetic disturbances) are mostly removed.

Two important problems have to be solved in preparing the final dataset of annual means. The first one is to get annual means for observatories which did not run throughout 1997. The second is to estimate the crustal biases.

Some observatories do not provide exact mean annual values for 1997.5 for various reasons: they were closed during that year, or they were run for a short while or they were closed before 1997 and new equipment was installed during that year. Two observatories were closed during 1997: GLN (annual mean from the first 85 days only, thereafter it was a variometer station), and MBC (observatory closed on day 174). In one observatory (AAE) new equipment was installed and data became available only from September 1997. To get the annual means the available data were extrapolated to 1997.5. In all, the data from 145 observatories were collected for this study.

The second important aspect relating to the preparation of the dataset is estimation of the crustal biases. It is known that some observatories are located on local anomalies that can exceed several hundred nanoTeslas (nT). To compute the crustal biases the annual mean value given by an observatory for the 1980.0 epoch was compared with the computed value (for the same location) from a model based on high quality vector data from the MAGSAT mission. We derived a model for 1980.0 using three models calculated from the quiet time data by Cohen (1989), i.e., 1979.871, 1980.027, 1980.120 epochs. Among the observatories listed in Table 1, only 114 observatories were operating during 1979–1980 (when changes in baselines occurred they have been applied). Three others changed their location since 1980 and the site corrections have not been supplied by the observatories, so we estimated these values (AAE, DIK, MIR). A few others were opened between 1980 and 1985, and we extrapolated data back to 1980 (AMS, CHD, CRP, CTA, DLR, ETT, FRN,

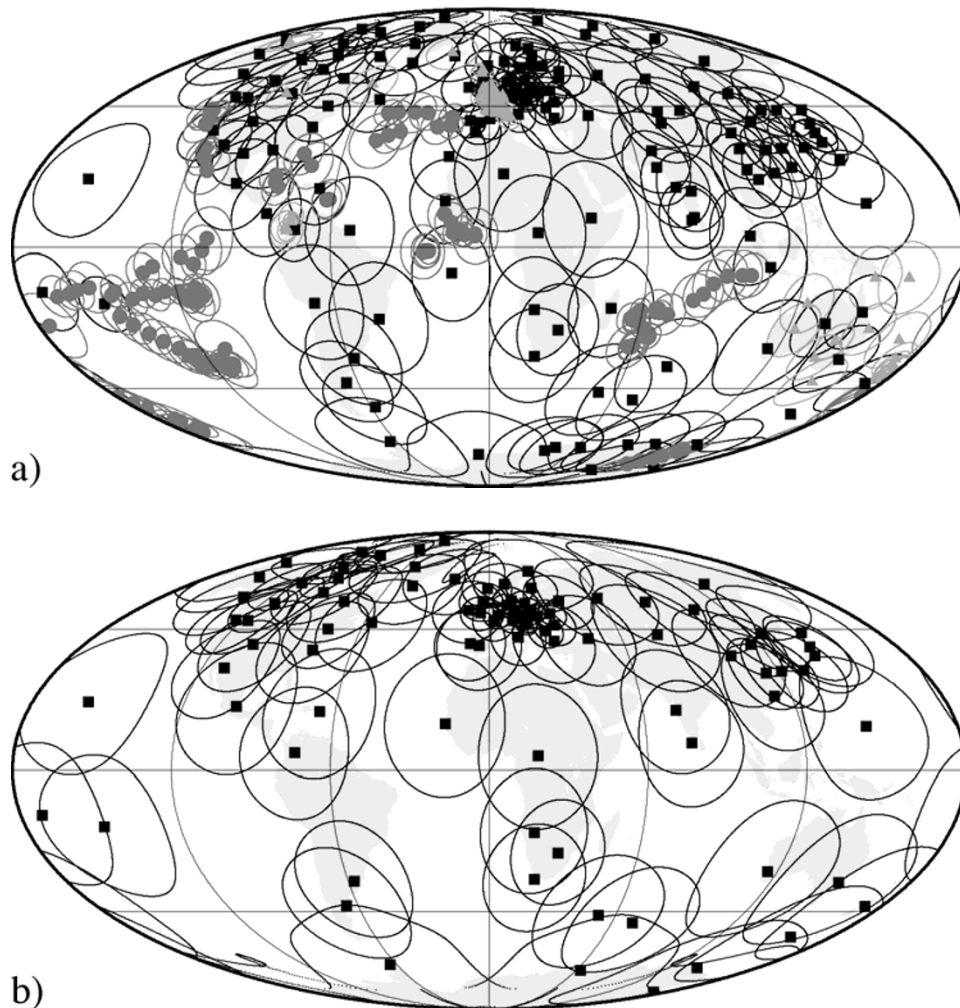


Fig. 1. a) Geographical distribution of the observations used in the main field modelling with their adopted weights: geomagnetic observatories (full black square), repeat stations (full pale grey triangle), scalar data (full grey circle). The weights are proportional here to the radius of circles around the observation points, and to a quality factor—1 for observatories and 3/4 for repeat stations and scalar data. b) Geographical distribution of the geomagnetic observatories used in the secular variation modelling with their adopted weights (proportional here to the radius of circles around the observation points). Mollweide equal area projection.

HTY, MZL, SPT and TTG). Also, the data for TAN were interpolated (linear interpolation).

For 16 observatories it was not possible to get mean values for 1980.0. We show later that these observatories are situated in areas without important magnetic anomalies, as indicated by the small magnitude of the absolute residuals with respect to our estimated 1997.5 model. Table 1 lists the crustal biases (X_{cc} , Y_{cc} and Z_{cc}), when computed.

The crustal biases, when available, were subtracted from each annual mean component. The final dataset was then converted to the geocentric coordinate system using the standard formulae (Langel, 1987).

2.1.2 Repeat station data Repeat stations are very useful in regional mapping. They are also very useful in global modelling, because of the reduced number of operating observatories in some large areas. The selected data were kindly provided by WDC Edinburgh, or directly by the national agencies. The repeat stations are generally re-occupied once every three to five years. For our purpose we retained only repeat stations occupied during 1997. Some of the available data were already reduced to the 1997.5 epoch.

The others were corrected assuming that the temporal change was the same as that at a nearby observatory.

All repeat station measurements were tested by comparison with our 1997.5 model (see Section 4), to eliminate those for which the absolute residuals from the model were greater than 250 nT in any component. The final repeat station dataset contained 67 observations, distributed as shown in Fig. 1.

2.1.3 Scalar data Some marine surveys were made during 1995–1998. Marine data were selected from periods when K_p indices were less than or equal to 2 $_{\sigma}$, and only measurements made during local night time were used, to mitigate the effects of diurnal variations. No data with absolute residuals larger than 500 nT with respect to our 1997.5 model were kept.

A map was then made of the selected data locations and from this it was decided that a 1° by 1° bin size was appropriate. For each bin a plot was made of total intensity versus time, and outliers were removed manually. The remaining data in the bin were averaged and adjusted to 1997.5 using the 1995.0–1999.0 secular variation models.

The marine data were provided by: CITHER 3 LEG2 in the Atlantic Ocean (February–April 1995), LARJAKA in the Indian Ocean (October–November 1995), PRIMAR96 survey, in the Romanche—equatorial Atlantic area (May 1996), FUJI-MD108 survey, in the south-west Indian rift area (October–November 1997), FOUNDATION-HOT-LINE survey, in the south Pacific area (January–February 1997), MD112/MAGOFOND2 survey in the central Indian rift area (October–November 1998). Some other data were found on GEODAS vol. 4—“LEG” cruises. Six scalar measurements were provided by a polar expedition from Dumont D’Urville to Vostok (January–February 1996). In total there were 139 scalar data averages, the locations of which are also plotted in Fig. 1.

2.2 Data selection for secular variation modelling

Our aim is to obtain a series of annual secular variation, obtained by differencing main field models based on observatory annual means. To verify these annual mean data, and to extrapolate beyond the published values, we used observatory monthly means.

2.2.1 Monthly means from geomagnetic observatories In our view, the best method to map temporal changes on a time-scale of years or decades is to use data from geomagnetic observatories. It is emphasised that no survey or satellite data can provide such information. Furthermore, with using only satellite data, it is not possible to distinguish between temporal and spatial variations of the field; and the main field variations on temporal scales greater than years cannot be defined by occasional satellite missions, since such variations are not linear. The present-day distribution of observatories is far from ideal, and its effect on modelling has already been noted (Alexandrescu *et al.*, 1994; Langel *et al.*, 1995). In the following, we describe the observatory data used and the problems related to this dataset.

Our purpose was to obtain a dataset with as many observatories as possible containing long series of measurements. To ensure the consistency of data, and the stability of our secular variation model in time, we chose those observatories for which annual mean values cover the last two solar cycles (from 1975 to present).

Moreover, for modelling the secular variation, it is important to get a dataset of very good quality and to be able to extrapolate these data over a time-span of two-three years. These are the reasons we also used a database of monthly means (Alexandrescu, 1998). This database covers a shorter time-span than the database of annual means (for most observatories from 1980, until at least 1997—the end of the series depending on each observatory). All the monthly mean values were adjusted to the last known reference point, when changes were pointed out by the observatory.

Thereafter, using monthly mean series over more than 18 years, it is possible to simply plot the variations of each component and to see the consistency of the data. In this way we identified and corrected various mistakes, and we discovered some other jumps; when this situation was noted more information was directly requested from the observatories. The last problem to solve in preparing the series of monthly means was time gaps. In these cases, linear interpolation was used to reconstruct the missing values. The largest gaps we corrected for were six months long, with three exceptions

(AIA, API, and TSU). Longer gaps of about 2 years were exceptionally accepted, because they were all situated in the Southern hemisphere (but, only after confirmation from the observatories about the use of the same configuration before and after the interruption).

In all, the dataset of monthly mean values contains 93 observatories. They are listed in Table 1, together with the corresponding IAGA code, geographical coordinates, the beginning and the end of the time series. The geographical distribution of these observatories is shown in Fig. 1.

2.2.2 Extrapolation of monthly means The first use of monthly mean values was to verify the annual means: we computed the annual means from monthly means and compared them with the annual means published by WDCs. When the differences were relatively small (± 5 nT) it was assumed they resulted from a different averaging procedure. However, for some observatories these differences were of the order of tens of nT. In all cases we asked for more information from the observatories, and we were able to find some sources of errors (sometimes wrong values tabulated in WDC files, sometimes different corrections which were not applied to monthly means, sometimes errors in initial computations).

The second use of monthly means was to extrapolate the available data over 2–3 years (depending on the end of each series) in order to reach 2000, the epoch of the IGRF candidate, and to cover the time-span from 1975 to 2000 for the secular variation models. To extrapolate the series we used exponential smoothing (Gardner, 1985). The specific formulae for simple exponential smoothing is:

$$s_t = \alpha * x_t + (1 - \alpha) * s_{t-1}, \quad (4)$$

where s_t , s_{t-1} is the smooth signal, and x_t the observed one. Consequently, each smoothed value is the weighted average of the previous observations, where the weights decrease exponentially depending on the value of parameter α . If α is equal to 1, then the previous observations are ignored entirely; if α tends to 0, then the current observation is ignored entirely. Also we added a twelve-month seasonal variation, in agreement with the annual variation of the field. This seasonal component is derived in a similar way to the s_t value from simple exponential smoothing. For this seasonal model we have:

$$I_t = I_{t-p} + \delta * (1 - \alpha) * e_t \quad (5)$$

where I_t is the seasonal component at time t , I_{t-p} is the smoothed seasonal factor at time $t - p$, p is the length of the period, and e_t is an error, i.e., the difference between the observed and the forecast value at time t . If δ is 0, a constant amplitude seasonal component is used to generate the one-step-ahead forecasts. If the δ parameter is equal to 1, then the seasonal component is modified “maximally” at every step by the respective forecast error; in most of the series analyzed δ was zero.

All available X , Y , Z components were fitted by this method, using a linear trend for most observatories (in some cases the exponential or damped trend had to be applied, when the series tendency was changing over the last part). All parameters were adjusted automatically, in a least squares sense. We show two examples of prediction, in Figs. 2 and 3.

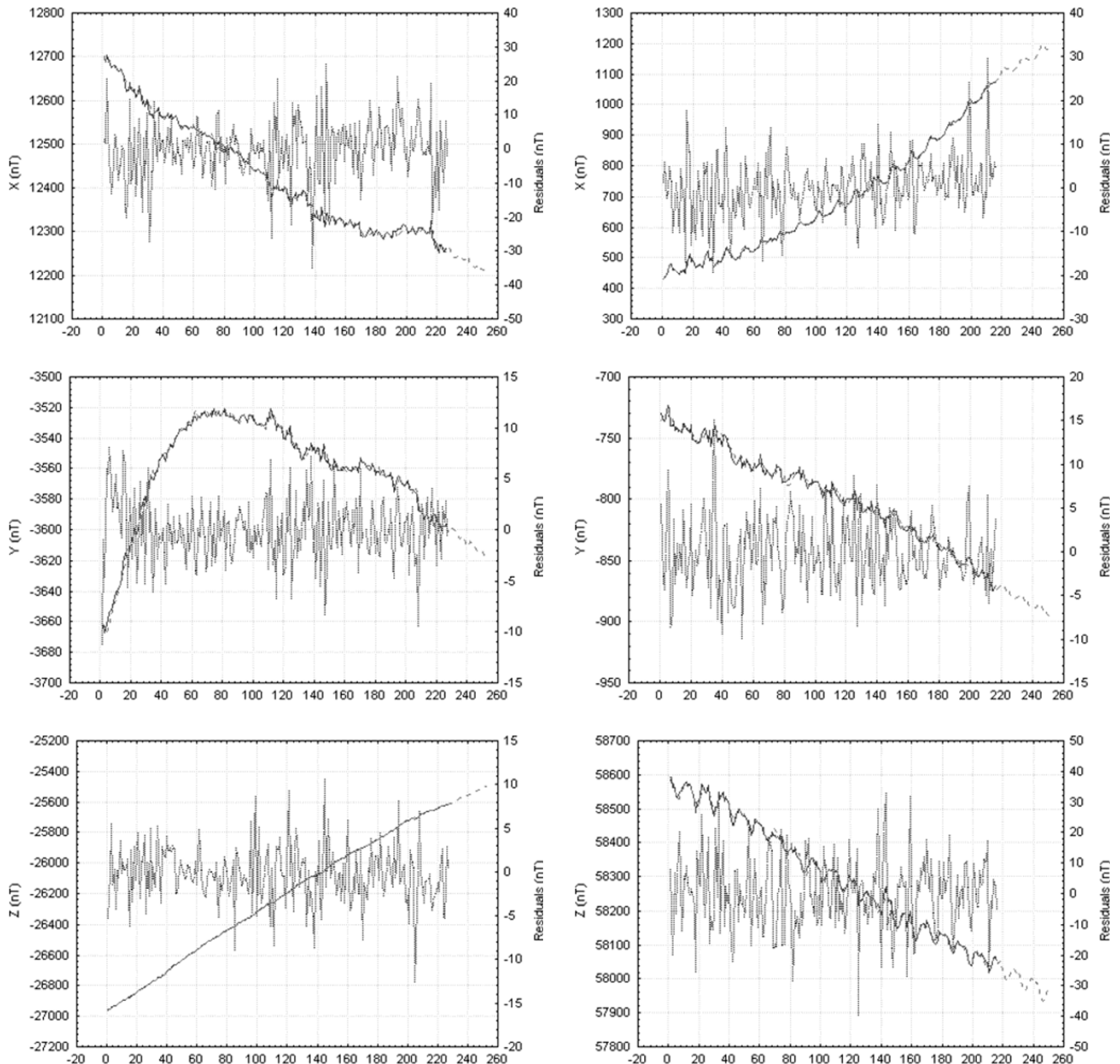


Fig. 2. Examples of measured series (full line), predicted values (dashed line) and residuals (dotted line) of the X , Y , Z monthly means for Hartebeesthoek observatory (HBK), from 1998.75 to 2000.92 (time scale is indicated by the number of observations on the abscissa of each graph). The parameters used to extrapolate the X , Y , Z components are $\alpha = 0.539$, 0.675 , 0.727 and $\gamma = 0.0$, 0.118 , 0.045 (see Subsection 2.2.2 for details).

Fig. 3. Examples of measured series (full line), predicted values (dashed line) and residuals (dotted line) of the X , Y , Z monthly means for Resolute Bay observatory (RES), from 1998.75 to 2000.92 (time scale is indicated by the number of observations on the abscissa of each graph). The parameters used to extrapolate the X , Y , Z components are $\alpha = 0.720$, 0.408 , 0.507 and $\gamma = 0.0$, 0.007 , 0.007 (see Subsection 2.2.2 for details).

3. Method of Analysis

For the main field model, epoch 1997.5 we used the dataset described in Subsection 2.1, and for the secular variation model 2000–2005 the datasets described in Subsection 2.2. All models were calculated using the least squares method of Cain *et al.* (1967). Also, we considered that the choice of the model for the first iteration has no importance in the final result, as it was shown recently (Ultré-Guéraud, 1996). Considering the available data distribution, the model for the main field was computed up to degree and order 10, and the models for the secular variation applied up to degree and order 8.

The *weighting scheme* applied to the geomagnetic obser-

vations is mainly based on the spatial distribution. Indeed, it is difficult to appreciate the quality of data provided by a given observation point because an important number of parameters which govern the field measurement cannot be parameterized (quality of instruments, operator experience, data processing, etc.).

The objective criterion in weighting data is to consider the geographical distribution of observation locations. For a given point, we search for all the other measurement positions situated in a circle of radius $(2 \cdot \pi \cdot a/2n)$, where a (6371.2 km) denotes the mean radius of the Earth, and n the maximum order of the spherical harmonic development; e.g., for the

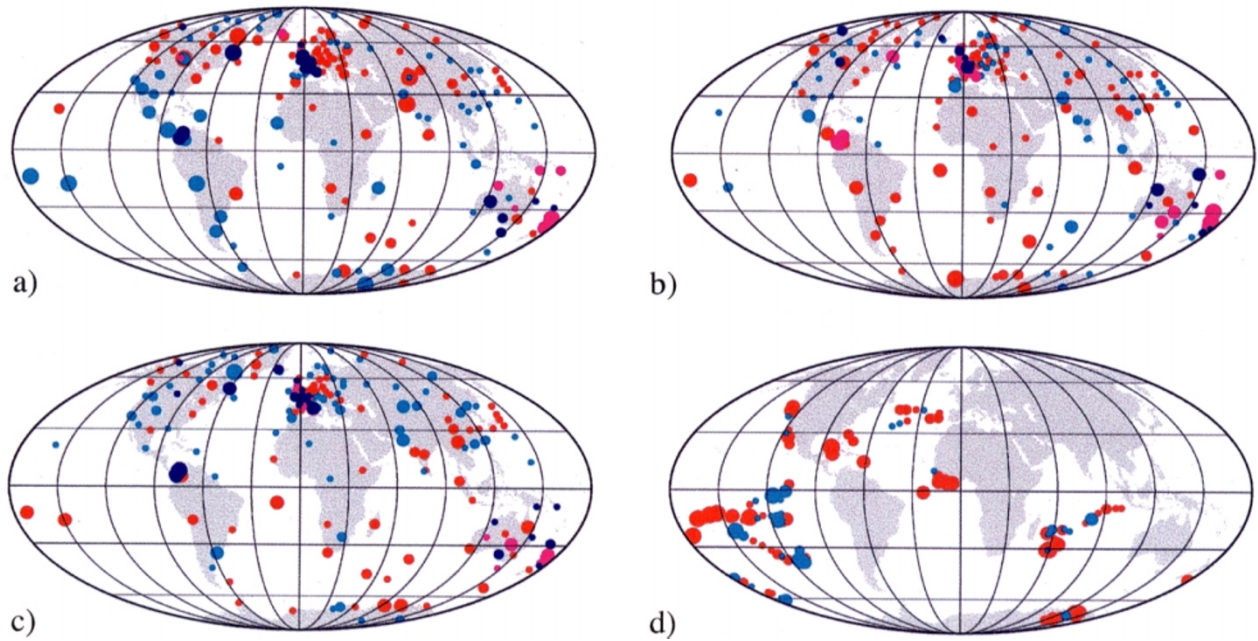


Fig. 4. Maps of residuals of the a) X , b) Y , c) Z , and d) F components at the Earth's surface for the main field model at 1997.5. The radius of circle are proportional to the absolute residuals: lower than 50 nT, between 50 and 100 nT, between 100 and 200 nT, and greater than 200 nT. Colors separate data sources and sign of residuals (negative/positive): observatory—light blue/red (X, Y, Z), repeat stations—blue/purple (X, Y, Z), scalar—light blue/red (F). Mollweide equal area projection.

main field model developed up to degree and order 10 the radius is about 2000 km. The circle represents the influence zone of the measurement on the model. This circle is divided into four quarters: south-east ($j = 1$), south-west ($j = 2$), north-west ($j = 3$) and north-east ($j = 4$) and then it can be written:

$$\omega_i = \frac{\omega'_i}{T} \quad (6)$$

$$\omega'_i = \frac{\sum_{j=1}^4 \min(d_j, d_{\max})}{4 \cdot d_{\max}} \cdot \gamma \quad (7)$$

$$T = \frac{\sum_{i=1}^N \omega'_i}{N}, \quad (8)$$

where ω_i is the weight for the i th observation, d_j is the distance between the observation i and the nearest one in the j th quarter, d_{\max} is the radius of the circle. The parameter γ makes the distinction between different classes of observation, as a quality factor: here its value is set to 1 for each observatory and 3/4 for repeat stations and scalar data.

This weighting scheme did not give too large a weight to one isolated observation, and it did not eliminate the observations situated in areas with a good coverage (i.e., Western-Europe). Some other schemes, based also on minimal distance between the observations, were also developed and tested. In order to choose the most efficient one, we computed and plotted the covariance matrices of parameters. The method described above ensured the best diagonality of the computed covariance matrices. Figure 1 shows also an equivalent of the adopted weights, expressed in kilometers around a given location.

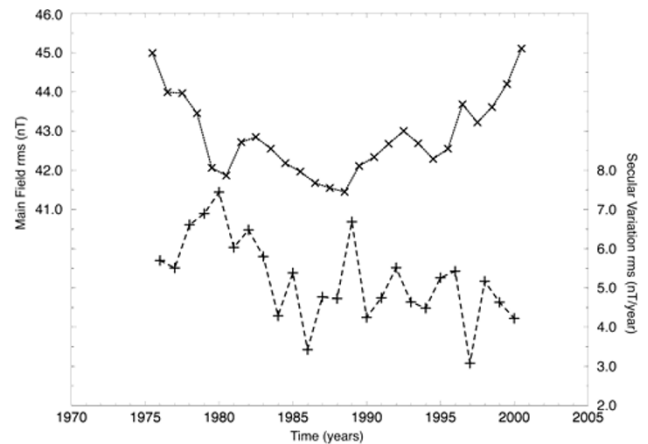


Fig. 5. Evolution of the root mean square residual (average over all components) for the MF (dotted line) and corresponding SV (dashed line) models from 1975 to 2000.

4. Results

4.1 A proposed main field model for the 2000.0 epoch

The main field model for the 1997.5 epoch was computed up to degree and order 10. It is known that there are contributions beyond this limit, but the available data could not support a higher extension.

To extrapolate this main field model to the 2000.0 epoch we updated the 1997.5 model by using the annual secular variation models described below. The list of Gauss coefficients of the main field for the 2000.0 epoch is presented in Table 2. The 120 coefficients obtained were rounded to the nearest nT.

The rms residual, average over all components, is 97 nT

Table 2. The Schmidt quasi-normalised main field coefficients (g_n^m and h_n^m) for 2000.0 and the secular variation ones (\dot{g}_n^m and \dot{h}_n^m) for 2000–2005 time-span.

Degree n	Order m	g_n^m (nT)	h_n^m (nT)	\dot{g}_n^m (nT year ⁻¹)	\dot{h}_n^m (nT year ⁻¹)
1	0	-29601	...	13.1	...
1	1	-1763	5173	9.3	-25.0
2	0	-2284	...	-12.2	...
2	1	3095	-2474	-0.4	-23.3
2	2	1658	-447	-2.0	-8.9
3	0	1337	...	1.7	...
3	1	-2288	-207	-4.1	7.3
3	2	1266	290	1.8	0.1
3	3	749	-471	-8.1	-14.9
4	0	958	...	-1.2	...
4	1	775	263	2.4	2.8
4	2	251	-234	-7.4	1.0
4	3	-416	121	4.1	6.4
4	4	110	-327	-2.7	-0.2
5	0	-221	...	-0.6	...
5	1	373	35	-0.9	-1.1
5	2	207	188	-3.0	0.2
5	3	-139	-134	-3.7	1.3
5	4	-158	-52	-0.7	2.9
5	5	-49	132	1.3	0.5
6	0	74	...	0.9	...
6	1	58	-5	-0.4	-0.1
6	2	68	34	0.3	-0.9
6	3	-150	60	2.6	0.7
6	4	-16	-49	-0.6	-0.4
6	5	34	-9	0.1	-0.0
6	6	-65	43	0.9	1.2
7	0	77	...	0.3	...
7	1	-103	-65	0.2	1.6
7	2	11	-23	0.4	-0.2
7	3	41	19	1.4	0.3
7	4	1	18	0.9	0.1
7	5	7	27	0.5	-1.4
7	6	12	-47	1.5	-0.5
7	7	-9	-13	-1.4	-0.2
8	0	18	...	-0.4	...
8	1	18	5	-0.1	-0.6
8	2	-1	-3	-0.5	0.1
8	3	-19	9	0.0	-0.2
8	4	-8	-29	-1.4	-0.1
8	5	16	9	0.0	1.0
8	6	11	15	-0.9	-0.9
8	7	-14	-6	-0.6	0.6
8	8	-17	5	-1.0	-0.4
9	0	4	...	...	...
9	1	29	-21	...	...

Table 2. (continued).

Degree n	Order m	g_n^m (nT)	h_n^m (nT)	\dot{g}_n^m (nT year ⁻¹)	\dot{h}_n^m (nT year ⁻¹)
9	2	-1	11	...	...
9	3	-17	3	...	...
9	4	3	-8	...	...
9	5	-14	1	...	...
9	6	-11	11	...	...
9	7	10	6	...	...
9	8	3	-28	...	...
9	9	-6	10	...	...
10	0	0	...	...	...
10	1	-16	8	...	...
10	2	-2	-10	...	...
10	3	2	4	...	...
10	4	3	9	...	...
10	5	8	-0	...	...
10	6	2	-11	...	...
10	7	2	-2	...	...
10	8	9	10	...	...
10	9	-15	0	...	...
10	10	6	-3	...	...

(respectively 101 nT, 67 nT, and 117 nT for observatory, repeat station, and scalar data). Figure 4 shows the residuals in X , Y , Z , F components for each point of observation for the 1997.5 epoch. The mean values for the components are -7 nT, 14 nT, and 11 nT in the observatories, -16 nT, 44 nT and 3 nT in the repeat stations, and 47 nT for the scalar measurements.

4.2 A proposed secular variation field for 2000–2005

To build the secular variation models over the 25-year time-span, we computed 26 main field models, from 1975 to 1997 (for the middle of each year). These models have been used to estimate the secular variation models, by taking successive differences.

To verify the consistency of the datasets and of the results, the rms residuals for the main field and secular variation are plotted in Fig. 5. For the main field model, the mean of the rms residuals is 43 nT, and for the secular variation models it is 5 nT · yr⁻¹. As is shown in Fig. 5, the two curves may be correlated. The decrease of the rms residual for the main field models at the beginning of the period could be due to the improvement in the data quality (no monthly means were available between 1975 and 1980 to verify the annual mean values). On the contrary, the increase of the rms residual at the end of the interval is not explained by the data quality, as monthly means were available up to the end of 1998 (for almost all observatories).

From these models we extracted separately each coefficient. In such a way, series for each coefficient (i.e., series of \dot{g}_1^0 , \dot{g}_1^1 , \dot{h}_1^1 , etc...) containing 25 values were produced.

To predict the time variation of these coefficients, we again used exponential smoothing. The prediction was not easy, because of the short length of the series. This was the reason

we preferred to take constant value of $\alpha = 0.5$ in the prediction procedure (Eq. (7)). Each series of coefficient was extrapolated to give five values, corresponding to the secular variation for 2001.0, 2002.0, 2003.0, 2004.0, and 2005.0. Finally, to predict a secular variation model for 2000–2005, we computed mean values for the 2002.5 epoch, as:

$$\dot{c}_{2002.5} = \left[\left(\frac{\dot{c}_{2000.0} + \dot{c}_{2005.0}}{2} \right) + \dot{c}_{2001.0} + \dot{c}_{2002.0} + \dot{c}_{2003.0} + \dot{c}_{2004.0} \right] / 5 \quad (9)$$

where \dot{c} represents a \dot{g}_n^m or \dot{h}_n^m . The coefficients of this 2002.5 model are listed in Table 2, rounded to 0.1 nT · yr⁻¹.

5. Conclusion

In our attempt to produce a geomagnetic main field model for 2000.0 and a secular variation one for the 2000–2005 time-span, we chose an approach which makes no direct links between our models and previous IGRF models. It is pertinent to ask how valid these coefficients are. To answer this question a test was done, separately for the main field and secular variation.

5.1 Evaluation of the proposed main field model

We compared our main field model with the published IGRF 1995 model. The IGRF 1995 model was extended to 1997.5, using our secular variation models. Taking the difference between the two models, areas with important discrepancies have been noted. In the most densely covered areas the differences are of some tens of nT. As expected the worst situation is encountered in areas without observations (e.g., South Atlantic or North Pacific). But there were also

large differences in areas where marine data were available for the main field model. For example, in the South Pacific the differences between the available marine data and those predicted by IGRF 1995 are about 1000 nT.

The large differences between our candidate model and the updated IGRF 1995 model show that the main geomagnetic field model has to be improved using the new Ørsted data. However at the time of these computation, data supplied by only the OverHauser magnetometer were available. Preliminary calculations using a part of this dataset showed that this improved our model. But, of course, vectorial data are really needed. With this new dataset a very good coverage of the Earth's surface will be realised.

5.2 Evaluation of the proposed secular variation model

We also tried to estimate the quality of our secular variation models, by checking the method of geomagnetic data prediction. For some observatories (chosen randomly), the last two years of monthly mean values were removed, and the same time-span was predicted. In all cases, predictions were in good agreement with data, except for the observatories where the secular variation rapidly changed.

The secular variation models would be improved if the data series were available from more observatories. In the present study, some observatories located in "key" areas like the Southern hemisphere are missing. However, the global network of geomagnetic observatories has a far from uniform distribution. So long as our knowledge of the secular variation depends heavily on observatory data, it will remain inaccurate. It is clear that new observatories are required, especially in ocean areas, and the long-term running of the observatories has also to be considered.

In the near future, new and exciting satellite missions (Ørsted, SAC-C, CHAMP) will investigate hitherto hidden features of the geomagnetic field. Only the combined analysis of data obtained by measurements at the Earth's surface and by satellites will drastically enhance the signal-to-noise ratio and extraction of the various sources of the field, en-

abling a unique separation to be made.

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B. Langlais (e-mail: langlais@ipgp.jussieu.fr) and M. Mandea (e-mail: mioara@ipgp.jussieu.fr)