GEOPHYSICAL RESEARCH LETTERS, VOL. 29, NO. 15, 10.1029/2001GL013693, 2002

Observatory crustal magnetic biases during MAGSAT and Ørsted satellite missions

Mioara Mandea and Benoit Langlais
Institut de Physique du Globe de Paris, France

Received 27 June 2001; revised 9 November 2001; accepted 13 November 2001; published 3 August 2002.

[1] Computing main-field models derived from MAGSAT and Ørsted satellite magnetic measurements, the crustal influence on satellite data can be treated as random noise. Satellite data can thus be used in conjunction with magnetic observatory measurements to isolate the non-core field at the observatory locations. Crustal biases for the horizontal northward *X*, eastward *Y* and vertical downward *Z* components are computed for all magnetic observatories where data are available for MAGSAT (1979–1980) and Ørsted (1999–2000) epochs, to study their correlation over twenty years. For a set of observatories installed after 1979 new crustal biases are computed. *INDEX TERMS:* 1532 Geomagnetism and Paleomagnetism: Reference fields (regional, global); 1545 Geomagnetism and Paleomagnetism: Spatial variations (all harmonics and anomalies); 1599 Geomagnetism and Paleomagnetism: General or miscellaneous

1. Introduction

[2] For determining the temporal variation of the internal field, measurements from magnetic observatories remain the most useful source of information. The use of observatory data in main-field modeling needs the crustal magnetic field contribution be taken into account. This is also true when using combined satellite and ground datasets. Omitting the crustal biases in modeling can lead to local errors of about 2000 nT (about 10% of the total field over some areas), affecting the large scales of the field (in the spherical harmonic analysis truncation). One method to avoid these artifacts is to use only the time derivative of the observatory measurements, i.e. the secular variation, the main field being derived from the satellite dataset [*Cain et al.*, 1983]. Applying this method, the ionospheric field contribution can not be estimated (simultaneous ground and satellite measurements are needed [*Langel et al.*, 1996]). Another method is to take into account the crustal magnetic biases, by solving them together with the Gauss coefficients [*Sabaka et al.*, 2001], or by computing and removing the a priori known crustal biases from the magnetic observatory measurements. The crustal biases are estimated by comparing the magnetic components measured in an observatory with those predicted by a geomagnetic model, truncated to its nuclear part (i.e., up to degree and order 13, based on the energy spectrum of the field [*Langel and Estes*, 1982]). The differences are considered as the signature of the crustal field with an induced or remanent origin. These short wavelength biases characterize the observatory area [*Langel et al.*, 1982; *Gubbins and Bloxham*, 1985; *Langel and Estes*, 1985; *Bloxham and Gubbins*, 1986]. The accurate determination of the observatory location is crucial, as well as the quality of the measurements. [*Langel et al.*, 1982] noted that the biases can be partly related to a poor knowledge of the position of the observatory, or to some problems linked to measurements.

[3] Some sets of crustal biases have been published, using MAGSAT data to model the geomagnetic field. These crustal bias sets have been computed using two slightly different approaches. The first one is a direct method: the observatory biases are the differences between the observatory annual mean values and the values predicted by a model computed only from satellite data, for the same spatial and temporal parameters [*Barraclough*, 1985; *Gubbins and Bloxham*, 1985; *Bloxham and Gubbins*, 1986; *Jackson*, 1989; *Ultré-Guérard*, 1996]. In this method the main-field model based on satellite data is assumed not to be affected by the local crustal biases. The second method is an inverse one: the crustal biases are considered as unknowns in inverting jointly satellite and observatory data [*Langel et al.*, 1982; *Langel and Estes*, 1985]. The observatory crustal bias is then the constant, non-modeled part of the observatory magnetic field measurement.

[4] In this study we compare the crustal biases computed for the MAGSAT epoch with new crustal biases re-evaluated using Ørsted-based models. We also compute the crustal biases for some new observatories installed after 1979.

2. Method and Data

[5] We consider that the internal field $\vec{B}_i$ at a given observatory location can be represented as the vector sum:

$$\vec{B}_i = \vec{B}_m + \vec{B}_c \qquad (1)$$

where $\vec{B}_m$ is the main (core) field and $\vec{B}_c$ is the crustal bias which may change appreciably over a distance of a few km.

[6] At the satellite altitude, the magnetic signature $\vec{B}_c$ of the short wavelength of lithospheric origin can be considered as a random noise with respect to the large wavelength of the core magnetic field $\vec{B}_m$. In this study we consider the satellite data free from the effects of the crustal fields and thereafter the biases (X_c, Y_c, Z_c) are computed as differences between the magnetic components (X_i, Y_i, Z_i) measured at the observatory and the components (X_m, Y_m, Z_m) predicted by a model based on satellite data.

[7] The method is applied for two-month satellite datasets: November and December 1979 for MAGSAT and November and December 1999 for Ørsted. The two-month period is chosen as a reasonable compromise between modeling errors due to an uneven geographical coverage [*Langlais and Mandea*, 2000] and errors due to the secular variation [*Langel and Estes*, 1985]. Moreover, considering the same period of the year it is not necessary to take into account the

0094-8276/02/2001GL013693$05.00

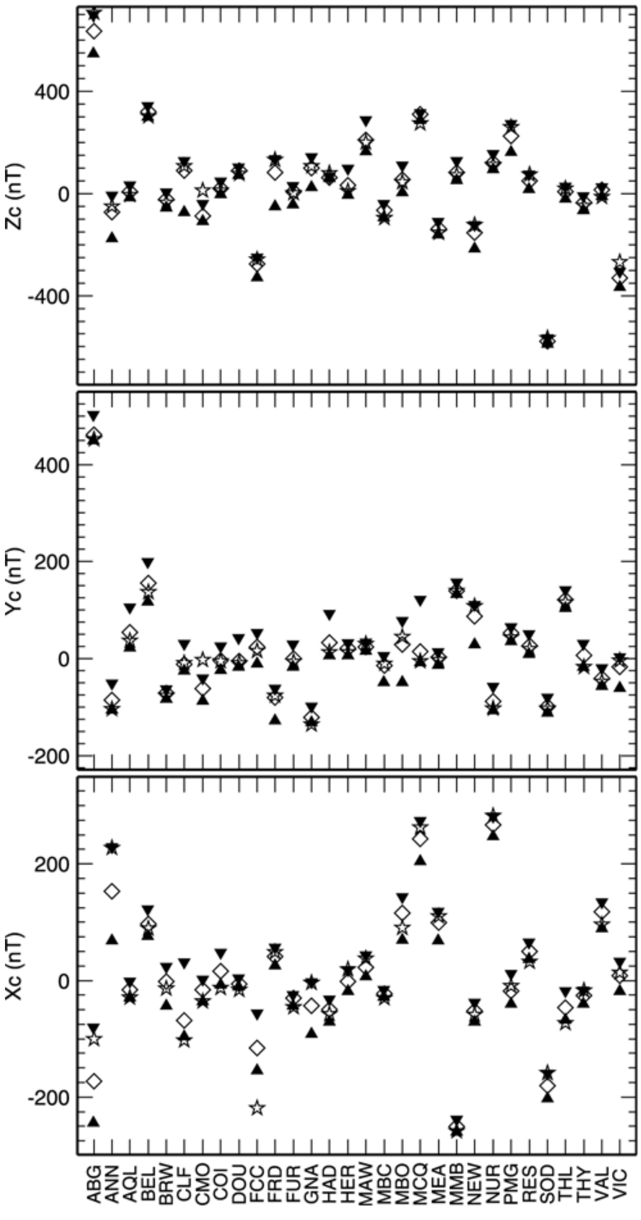

Figure 1. The observatory crustal biases determined in the present study (star); the minimum value (triangle up), maximum value (triangle down) and the mean of the eight available sets (diamond) are also indicated.

annual and semi-annual external variations. Main-field models are denoted as M19791112 and Ø19991112 as described in [*Langlais et al.*, 2002]. Noting t the associated time in hour of a satellite measurement, the selection criteria were $Kp(t) \leq 1^+$, $Kp(t \pm 3) \leq 2^-$, $|Dst| \leq 5$ nT, $|d(Dst)/dt| \leq 3$ nT.hour^{-1}. Only night time data were kept (0600 LT for MAGSAT, 2200 LT for Ørsted). Finally, data were sorted to get their geographical distribution as equiangular as possible.

[8] Observatory daily mean values, for all three components and available over the same two months as the satellite data, were obtained from the WDC - Copenhagen, Denmark, or directly from the observatories. All data have been screened to assert their validity. We checked the consistency of data [*Alexandrescu*, 1998] using the available daily or monthly mean values over the 1979–1999 period. This revealed that in some observatories changes in the baseline levels occurred between 1979 and 1999, and they were applied. All daily mean values were then averaged to obtain two-month mean values for the epochs 1979.92 and 1999.92.

3. Results

[9] Crustal magnetic field may be of induced or remanent origin. We here assume a purely remanent field, which is expected to be constant over time. Magnetic crustal biases computed from two independent satellite-based models should thus be equivalent. However, accurate determination of the crustal biases highly relies on the capability of the model to well describe the main magnetic field. Two distinct main-field models, for two different epochs, computed with the same parameters ensure a more credible estimation and comparison of the crustal biases.

[10] We first compare the observatory magnetic biases published by different authors [*Langel et al.*, 1982; *Barraclough*, 1985; *Gubbins and Bloxham*, 1985; *Langel and Estes*, 1985; *Bloxham and Gubbins*, 1986; *Langel*, 1987; *Jackson*, 1989; *Ultré-Guérard*, 1996] with the biases computed in this study. Only 30 observatories are common to all. Figure 1 shows this comparison: for each observatory and component, the minimum, maximum and mean crustal biases are plotted, together with the value computed in this study, based on the MAGSAT model. The rms and the correlation coefficients between previously computed crustal biases and those computed in this study for the MAGSAT epoch are presented in Table 1. Except for a few differences (FCC for X_c, CMO for Y_c, CMO and VIC for Z_c), all our estimations are within the interval delimited by the minimum and maximum previous computed biases. It is also worth noting that these intervals may be large, as for ABG, ANN and FCC for X_c, and for ABG, ANN and FRD for Z_c ($\simeq$200 nT). The observed differences may be related to the different methods used by the authors. Another explanation may be the change in the observatory position, or the use of different coordinates. For example, the location of GDH observatory (not shown on Figure 1) changed of a few tens of kilometers in 1976. Some authors computed the crustal biases for the first site [*Langel et al.*, 1982; *Gubbins and Bloxham*, 1985], some others for the second [*Jackson*, 1989; *Ultré-Guérard*, 1996]. We strongly recommend that crustal biases are published with the coordinates used.

[11] A more interesting result is obtained when computing the crustal biases for the MAGSAT and Ørsted epochs. We consider 62 observatories for which data are available

Table 1. Comparison With Previous Studies

Study	σ_X [a]	σ_Y [a]	σ_Z [a]	C_X [b]	C_Y [b]	C_Z [b]
[1]	27.7	23.2	42.6	0.974	0.977	0.981
[2]	41.5	22.7	39.9	0.940	0.981	0.982
[3]	28.3	15.2	31.3	0.973	0.990	0.990
[4]	34.0	13.3	35.2	0.963	0.992	0.987
[5]	58.3	41.9	62.2	0.873	0.929	0.959
[6]	27.5	23.2	42.0	0.974	0.977	0.982
[7]	62.8	37.4	72.3	0.851	0.942	0.949
[8]	21.0	13.3	27.1	0.985	0.992	0.992

[1] [*Langel et al.*, 1982]; [2] [*Barraclough*, 1985]; [3] [*Gubbins and Bloxham*, 1985]; [4] [*Langel and Estes*, 1985]; [5] [*Bloxham and Gubbins*, 1986]; [6] [*Langel*, 1987]; [7] [*Jackson*, 1989]; [8] [*Ultré-Guérard*, 1996].
[a] rms misfits in nT.
[b] Correlation coefficients.

Table 2. Observatories Considered in the Present Study

Observatory			X_c		Y_c		Z_c	
Code[a]	λ[b]	φ[c]	M[d]	Ø[d]	M[d]	Ø[d]	M[d]	Ø[d]
AAA	43.15	76.55	79	29	−2	3	−62	−54
ABG	18.64	72.87	−100	−94	451	439	707	686
API	−13.81	188.23	−48	−31	212	204	−872	−886
BEL	51.84	20.79	89	89	137	148	303	313
BFE	55.63	11.67	62	52	−87	−97	−182	−180
BLC	64.33	263.97	128	150	−62	−37	−80	−78
BNG	4.44	18.57	−173	−161	−27	7	234	202
BOU	40.14	254.76	−41	−60	48	31	−193	−162
BRW	71.32	203.38	−13	16	−76	−62	−34	−14
CBB	69.20	255.00	74	87	−87	−99	95	131
CLF	48.02	2.27	−102	−103	−9	−15	106	112
CMO	64.86	212.16	−36	−15	−1	−2	10	−13
CZT	−46.43	51.87	−774	−767	1088	1090	142	154
DOU	50.10	4.69	−15	−13	−9	−17	77	82
DRV	−66.67	140.01	−138	−119	−429	−382	−2820	−2837
ESK	55.32	356.80	2	−4	−47	−41	−60	−49
FCC	58.67	265.91	−218	−183	15	60	−259	−231
FRD	38.21	282.63	48	38	−75	−59	131	142
FUQ	5.47	286.26	65	107	−56	−38	72	71
FUR	48.17	11.28	−45	−42	−5	−1	1	2
GDH	69.25	306.47	255	244	−293	−301	749	762
GNA	−31.78	115.95	−3	−37	−135	−107	108	102
GUA	13.58	144.87	98	96	83	66	56	59
HAD	51.00	355.52	−57	−66	13	14	79	80
HBK	−25.88	27.71	77	46	−18	0	77	35
HER	−34.43	19.23	19	3	13	15	10	11
HLP	54.61	18.82	38	23	−164	−166	−89	−86
HON	21.32	202.00	−188	−191	81	82	−329	−311
HRB	47.87	18.19	−14	−5	−18	−21	−49	−76
KAK	36.23	140.19	−26	−26	7	2	−83	−85
KNY	31.42	130.88	−35	−30	52	54	−36	−32
LER	60.13	358.82	−123	−133	172	164	34	55
LRV	64.18	338.30	−279	−281	596	594	−469	−468
MAW	−67.61	62.88	38	43	30	−12	199	191
MBO	14.39	343.04	90	81	45	37	45	62
MCQ	−54.50	158.95	263	267	−5	10	274	282
MEA	54.62	246.67	110	80	−2	14	−152	−150
MMB	43.91	144.19	−257	−252	139	139	71	65
NEW	48.26	242.88	−59	−61	108	105	−122	−127
NGK	52.07	12.68	−50	−44	4	5	−77	−78
NUR	60.51	24.66	282	278	−102	−99	112	115
NVS	55.03	82.90	170	182	−88	−93	−12	0
OTT	45.40	284.45	107	111	−156	−143	161	148
PAF	−49.35	70.26	446	434	−146	−136	−357	−324
PBQ	55.28	282.26	94	129	386	343	34	79
PPT	−17.57	210.43	−720	−738	−969	−957	76	91
RES	74.70	265.10	32	34	20	21	73	125
SBA	−77.85	166.78	−2211	−2190	−906	−924	−3751	−3683
SIT	57.06	224.68	−12	−11	−19	−14	−49	−69
SJG	18.11	293.85	−81	−88	183	143	172	156
SOD	67.37	26.63	−159	−175	−101	−104	−566	−583
STJ	47.60	307.32	41	23	20	32	16	25
SUA	44.68	26.25	−15	−4	−32	−18	−58	−55
TFS	42.09	44.71	−283	−261	2	−3	−95	−114
THL	77.48	290.83	−72	−75	116	88	19	45
THY	46.90	17.89	−16	−48	−17	−4	−47	−50
TSU	−19.22	17.70	52	21	−71	−43	111	80
TUC	32.25	247.17	−173	−185	−534	−556	884	873
VAL	51.93	349.75	95	95	−47	−56	−12	−14
VIC	48.52	236.58	13	−3	−3	−1	−267	−269
WNG	53.74	9.07	33	34	50	49	−72	−70
YKC	62.48	245.52	−23	−14	−52	−47	−172	−157

[a] According to the IAGA convention.
[b] Latitude of the observatory, in degrees.
[c] Longitude of the observatory, in degrees, positive eastward.
[d] Crustal biases for MAGSAT (M) or Ørsted (Ø) epoch, in nT.

for both epochs (Table 2). Correlations between the biases computed for each magnetic component are presented in Table 3. The obtained crustal biases for 1979 and 1999 are as close as 20 nT for 85% of the observatories. Considering CLF observatory, for which the changes in the magnetic environment are well-known by us, the differences between the crustal biases are 0, −6, 5 nT, infor the X_c, Y_c, Z_c. The largest differences are 49 nT in X_c (AAA), 46 nT in Y_c (DRV) and 58 nT in Z_c (SBA). These differences may be related to the external magnetic perturbations as the two epochs (1979.92 and 1999.92) are near the solar maximum: the averaged a_p indices are 10 and 9 in November and December 1979, compared with 14 and 10 in 1999; mean *Dst* values over these periods are −7 and −13 nT, corresponding to changes in the magnetic field of about 1–2 nT.

[12] Finally, we compute the crustal magnetic biases for the observatories installed between 1979 and 1999. These new crustal biases are presented in Table 4. Some of these observatories are crucial in main-field modeling, as they are located in regions with a paucity of observatories (AMS, CTA, SPT). Furthermore, some biases are very large, and their omission could lead to large modeling errors.

4. Conclusions

[13] Detailed studies of the crustal biases are important when observatory data are used in geomagnetic field modeling. Thus it is important to remove these crustal biases from the observatory data to avoid modeling errors when using combined observatory and satellite datasets. In this study we compute the observatory crustal biases a posteriori the model generation. Our comparison of published crustal biases indicates that the crustal field is larger in *Z* than in the other elements. Not surprisingly, the most important differences between the biases previously published are found for this component. This could be the signature of induced field. However, when analyzing the bias evolution ($\Delta\vec{B}_c$) versus the field evolution ($\Delta\vec{B}_m$) or the magnetic latitude, no clear relationship is found.

[14] The new biases computed using the Ørsted model are very close to the ones computed with the MAGSAT model, supporting the idea that the crustal field did not change over the last twenty years. Clearly the computation of crustal biases relies not only on the observatory measurement quality but on the quality of the satellite-based model.

[15] A possible improvement in estimating the crustal biases is the use of "quiet" monthly means, i.e. based on the five quietest days per month. Such dataset would help in separation of induced and remanent contributions. This test requires more work in obtaining the data from observatories, and will be the subject of further study.

Table 3. Comparison of 1979 and 1999 Crustal Biases

	X_c			Y_c			Z_c		
R[a]	N[b]	σ[c]	C[d]	N[b]	σ[c]	C[d]	N[b]	σ[c]	C[d]
1	62	17.6	0.999	62	17.4	0.998	62	20.0	0.999
2	59	17.6	0.991	57	17.7	0.993	55	18.4	0.993
3	51	17.8	0.978	52	16.1	0.980	47	18.0	0.983
4	37	17.0	0.949	40	15.7	0.939	30	16.3	0.964

[a] Considered ranges: (1) all, (2) ±500 nT, (3) ±200 nT, (4) ±100 nT.
[b] Number of observatories within the range.
[c] rms misfits in nT.
[d] Correlation coefficients.

Table 4. New Observatories Considered in the Present Study

Code[a]	Year	λ[b]	φ[c]	X_c[d]	Y_c[d]	Z_c[d]
AMS	1981	−37.833	77.567	−597	−661	−1985
ASP	1992	−23.761	133.883	16	−19	35
BSL	1986	30.400	270.400	−86	45	36
CTA	1984	−20.088	146.254	−472	−101	176
DLR	1982	29.483	259.083	83	86	75
FRN	1982	37.083	240.283	−46	−27	−209
GUI	1993	28.321	343.559	−3149	−821	−475
IQA	1995	63.750	291.482	157	−11	−297
KOU	1996	5.300	307.200	80	92	−159
PHU	1985	21.100	105.900	2	−4	−122

[a] According to the IAGA convention.
[b] Latitude of the observatory, in degrees.
[c] Longitude of the observatory, in degrees, positive eastward.
[d] Crustal biases, in nT.

[16] **Acknowledgments.** The authors would like to thank the staff of the geomagnetic observatories for their kind supplying of high-quality data. The Ørsted satellite is funded by the Danish Ministry of Transport, the Ministry of Research and Information Technology and the Ministry of Trade and Industry. Additional support was provided by the National Aeronautics and Space Administration, the European Space Agency, Centre National d'Etudes Spatiales and Deutsche Agentur Für Raumfahrtangelegenheiten. This is IPGP contribution number 1836.

References

Alexandrescu, M., Database of Geomagnetic Observatory Monthly Means Seeks Contributors, *EOS*, *79*, 345, 1998.
Barraclough, D. R., A comparison of satellite and observatory estimates of geomagnetic secular variation, *J. Geophys. Res.*, *90*, 2523–2526, 1985.
Bloxham, J., and D. Gubbins, Geomagnetic field analysis IV, Testing the frozen flux hypothesis, *Geophys. J. R. Astron. Soc.*, *84*, 139–152, 1986.
Cain, J. C., J. Frayser, L. Muth, and D. Schmitz, The use of Magsat data to determine secular variation, *J. Geophys. Res.*, *88*, 5903–5910, 1983.
Gubbins, D., and J. Bloxham, Geomagnetic field analysis, III. Magnetic fields on the core-mantle boundary, *G. J. R. Astr. Society*, *80*, 695–713, 1985.
Jackson, A., The Earth's magnetic field and the core-mantle boundary, Ph.D. thesis, University of Cambridge, 1989.
Langel, R. A., The Main Field, in *Geomagnetism*, vol. 1, edited by J. A. Jacobs, Chap. 4, Academic Press, London, UK, 1987.
Langel, R. A., and R. H. Estes, A geomagnetic field spectrum, *Geophys. Res. Lett.*, *9*, 250–253, 1982.
Langel, R. A., and R. H. Estes, The near-Earth magnetic field at 1980 determined from MAGSAT data, *J. Geophys. Res.*, *90*, 2495–2509, 1985.
Langel, R. A., R. H. Estes, and G. D. Mead, Some new methods in geomagnetic field modeling applied to the 1960–1980 epoch, *J. Geomag. Geoelectr.*, *34*, 327–349, 1982.
Langel, R. A., T. J. Sabaka, R. T. Baldwin, and J. A. Conrad, The near-Earth magnetic field from magnetospheric and quiet-day ionospheric sources and how it is modeled, *Phys. Earth Planet. Inter.*, *98*, 235–267, 1996.
Langlais, B., and M. Mandea, An IGRF candidate main geomagnetic field model for epoch 2000 and a secular variation model for 2000–2005, *Earth, Planets and Space*, *52*, 1137–1148, 2000.
Langlais, B., M. Mandea, and P. Ultré-Guérard, High-resolution magnetic field modeling: Application to MAGSAT and Ørsted data, *Phys. Earth Planet. Inter.*, in press, 2002.
Mandea, M., and B. Langlais, Use of Ørsted scalar data in evaluating the pre-Ørsted main field candidate models for the IGRF 2000, *Earth, Planets and Space*, *52*, 1167–1170, 2000.
Sabaka, T., N. Olsen, and R. A. Langel, A Comprehensive Model of the Quiet-Time, Near-Earth Magnetic Field: Phase 3, *Geophys. J. Int.*, submitted, 2001.
Ultré-Guérard, P., Du paléomagnétisme au géomagnétisme spatial: Analyse de quelques séquences temporelles du champ magnétique terrestre, Ph.D. thesis, Institut de Physique du Globe de Paris, 1996.

M. Mandea and B. Langlais, Institut de Physique du Globe de Paris, B.P. 89, 4 Place Jussieu, 75252 Paris cedex 5, France (mioara@ipgp.jussieu.fr)