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Observatory crustal magnetic biases during CHAMP satellite mission

G. Verbanac[1], **M. Mandea**[2], **M. Bandić**[3], **and S. Subašić**[4]

[1]Department of Geophysics, University of Zagreb, Horvatovac 95, Zagreb, Croatia
[2]Centre National d'Etudes Spatiales 2 Place Maurice Quentin, 75039 Paris, France
[3]Preziosastr. 15a, 81927 Munich, Germany
[4]Vukomerec 41, 10000 Zagreb, Croatia

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Correspondence to: G. Verbanac (giuli1.verbanac@gmail.com)

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Abstract

Taking advantage of nine years of CHAMP satellite mission (June 2000–August 2009), we investigate the temporal evolution of the observatory monthly crustal magnetic biases. To determine biases we compute *X* (northward), *Y* (eastward) and *Z* (vertically downward) monthly means from 42 observatory one-minute or hourly values, and compare them to synthetic monthly means obtained from a GRIMM3 core field model (V. Lesur, personal communication, 2014). Both short period variations and long term trends in the monthly bias time series are analyzed. A comparison with biases based on MAGSAT and Ørsted satellite data, related to the 1979.92 and 1992.92 epochs is performed. Generally, the larger biases averaged over nine years and the larger differences between biases based on different models are found in *Z* component. This can be the signature of the induced magnetic fields. Although annual trends in most bias series are observed, no clear evidence that the constant crustal field changed significantly over the studied period is found. Time series of monthly biases exhibit distinct oscillatory pattern in the whole time span, which we assign to the external field contributions. The amplitudes of these variations are linked with the phase of the solar cycle, being significantly larger in the period 2000–2005 than in the period 2006–2009. Clear semi-annual variations are evident in all components, with extremes in spring and fall months of each year. Common external field pattern is found for European monthly biases. A dependence of the bias monthly variations on geomagnetic latitudes is not found for the non-European observatories.

The results from this study represent a base to further exploit the observatory and repeat stations magnetic biases together with the data from the new satellite mission SWARM.

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1 Introduction

Measured at any point on the Earth's surface the magnetic field is a combination of several magnetic contributions generated by various sources. These fields are superimposed on and interact with each other. Dominant part of the Earth's magnetic field, core field (Jacobs, 1987; Merill et al., 1998), is internal in origin and is due to the electric currents in the Earth's outer fluid core. This part of the field varies over time scales of some months to decades and longer. The crustal field, related to the remanent and induced magnetization of the rocks within the crust (e.g., Mandea and Thèbault, 2007), is also internal in origin. The magnitude of the crustal field varies from fractions to hundreds of nT, but can reach values as high as several thousands of nT. The external fields are produced by ionospheric and magnetospheric current systems (e.g., Campbell, 2003). The values of those fields at the Earth's surface are of a few tens of nT, even a few hundred to thousand nT during magnetic storms. The external fields vary in time with periods less of second to the well known solar cycle (11 years) and its harmonics. Other important contributions are the magnetic fields induced by currents that flows in the crust and upper mantle. For an accurate determination of the core field and its temporal variation, it is essential to use geomagnetic observatory data, reprocessed for reflecting as well as possible the core contribution. Thus, contributions of other sources, have to be determined and taken into account. Note that omitting the possible crustal field contributions (crustal biases) may lead to errors of about 10 % of the field for the large scales (Langel and Hinze, 1998).

To determine the crustal biases two different methods have been used over the last years. One is to estimate the biases directly as additional unknowns fitting process when inverting observatory and satellite data for a spherical harmonic model (Langel et al., 1982; Sabaka et al., 2002). The other method is to compare the magnetic components measured at the observatory to values predicted by a model obtained from satellite data only (e.g., Gubbins and Bloxham, 1985; Bloxham and Gubbins, 1986). Most of the published biases are related to the specific epochs, being computed from

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one or several months of satellite data (Mandea and Langlais (2002) and the references therein). Nevertheless, some studies also investigated the temporal changes of the crustal biases over longer periods, when comparing the observatory annual means with models that cover different epochs (Verbanac et al., 2007a).

In this study we analyze monthly crustal bias evolutions of the X (northward), Y (eastward) and Z (vertically downward) magnetic components at 42 observatories. The paper is organized as follows. After this introduction, Sect. 2 describes the theoretical framework of this study, as well as the used datasets. Monthly biases over the nine years of CHAMP satellite mission (June 2000–August 2009) are calculated by comparing the observatory data to the core field predictions given by the GRIMM3 model (V. Lesur, 2014, personal communication). In the following we present the results and a comparison with biases based on MAGSAT and Ørsted satellite data, related for the 1979.92 and 1992.92 epochs. Discussions on the obtained results and conclusions are indicated in the last section.

2 Method and data

We consider that the geomagnetic field at a given time and observatory location, $\boldsymbol{B}_{\text{obs}}$, can be represented as the vector sum:

$$\boldsymbol{B}_{\text{obs}} = \boldsymbol{B}_{\mathbf{m}} + \boldsymbol{B}_{\text{c, rem}} + \boldsymbol{B}_{\text{c, ind}} + \boldsymbol{B}_{\mathbf{e}} \tag{1}$$

where $\boldsymbol{B}_{\mathbf{m}}$ is the main (core) field, $\boldsymbol{B}_{\text{c, rem}}$ is the remanent crustal field, $\boldsymbol{B}_{\text{c, ind}}$ is the induced crustal field and $\boldsymbol{B}_{\mathbf{e}}$ is the external field.

We define the crustal biases $\boldsymbol{B}_{\mathbf{c}}$:

$$\boldsymbol{B}_{\mathbf{c}} = \boldsymbol{B}_{\text{c, rem}} + \boldsymbol{B}_{\text{c, ind}} + \boldsymbol{B}_{\mathbf{e}} \tag{2}$$

as we cannot directly distinguish between these different contributions.

With the assumption that in the geomagnetic core models obtained from satellite data the effects of both external and crustal fields are minimized as much as

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possible, we compute the crustal biases (X_c, Y_c, Z_c) as differences between the magnetic components measured at the observatories ($X_{obs}, Y_{obs}, Z_{obs}$) and the same components calculated from a satellite-based model (X_m, Y_m, Z_m).

The described method is applied to monthly means of all three magnetic components.

One dataset consists of the monthly means computed from the available continue measurements at magnetic observatories, from June 2000 to August 2009. For 42 geomagnetic observatories, the monthly averages are calculated from one-minute values or hourly values when the one minute values are not available.

The initial datasets were obtained from INTERMAGNET (http://www.intermagnet.org) and WDC Edinburgh (http://www.wdc.bgs.ac.uk). Monthly means were calculated only if more than 90 % of the one-minute or hourly values were available, ensuring the reliability of our final monthly means dataset. We carefully checked the availability, quality and continuity of the observatory data over the studied period. All the changes of the observatory locations and data discontinuities (jumps) reported in their annual mean values are taken into account by adjusting the geomagnetic measurements to the level of the most recent epoch.

The second dataset is based on synthetic monthly means estimated for the same observatory locations and for the same time span as above from a magnetic field model, here GRIMM3.

3 Results

We first compute the average of the bias for each observatory over nine years (June 2000 to August 2009) in order to get an order of magnitude of the constant crustal field contributions at different locations. The averaged biases for all considered observatories with the corresponding standard deviations (SD) are indicated in Table 1. The solid line separates the non-European from the European observatories. Most of the averaged biases for all three components are lower than ±200 nT. For X

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and Y components, a number of observatories shows very low biases. For the Z component, more commonly are the larger biases. Observatories having large biases in all components are LRV, PPT and SBA. The maximum bias in both X and Z appears at SBA (−2204 and −3748 nT, respectively), and in Y at PPT (−1039 nT). Let us note here that the European CM4-based biases averaged over 42 years (1960–2001) presented by Verbanac et al. (2007a) are also mostly lower than ±200 nT, and the largest values are again found in Z.

To gain a better understanding of the crustal biases evolution, we compare biases computed in this study with MAGSAT and Ørsted based biases calculated by Mandea and Langlais (2002) for 39 observatories common to both studies. Since MAGSAT and Ørsted biases are given for epochs 1979.92 and 1999.92 respectively, we further compute average biases over the studied period by using only November and December values of each year. For most of observatories, the averaged biases are in good agreement with both MAGSAT and Ørsted biases, the differences between them being within the range of the SD of averaged biases. At NVS observatory, biases at 1979.92 and 1999.92 epochs differ significantly from our averaged biases. We note that the larger disagreement found at PPT is due to data discontinuity (jump) in 2002.2. We applied the corrections of 221, 94, 479 nT in X, Y and Z, respectively. Further, note that the biases at PPT are important because in the vicinity of sensor there are large spatial gradients in the magnetic field.

At some observatories the differences between biases are about 10 nT larger than the SD of averaged bias values. Most of them are found in Z. We note that for some of these observatories (e.g. ABG, FCC) MAGSAT and Ørsted biases calculated by Mandea and Langlais (2002), differ from those published by other authors (e.g., Langel et al., 1982; Gubbins and Bloxham, 1985; Bloxham and Gubbins, 1986; Langel, 1987). Several contributions can be invoked to explain these differences in biases: different core field descriptions of the models, different methods and different observatory coordinates used in different studies, data errors or possible real changes in crustal magnetizations. Since the larger biases averaged over nine years are mainly in Z

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component, and the differences between biases at various epochs are also observed in this component, it seems likely that they might be the signature of an magnetic induced field.

At all locations, we examine both the long term trends and short period variations in bias time series. The annual trends in most bias series are noticed. Generally, they lie within the SD of the averaged biases, so no clear evidence that the constant crustal field changed significantly over the studied period is found. However, considering years in the late declining phase and minimum of the solar cycle 23, the trends are more clearly seen, as the external field contribution is minimized. Slightly increasing (in X) and decreasing (in Z) trends within these four years (2006–2009) are often in the order of 20 nT, and are rarely noticed in Y. Let us note here that Verbanac et al. (2007a) also identified clear long term trends at several locations when examining the European observatory biases over the 42 years (1960–2002).

Generally, for all components the temporal variations clearly show the semi-annual variation pattern, which we assign to the external field contributions. There seems to be external field effects of even shorter time scale. The amplitudes of semi-annual variations are remarkably larger in the period 2000–2005 than in the period 2006–2009. In the first period they approximately amount for 30–75 nT in X, 5–30 nT in Y, and 10–75 nT in Z. From 2006 to 2009, the amplitudes reach 10–40 nT in X, 0–20 nT in Y, and 5–60 nT in Z. The variation patterns at neighboring observatories are remarkably similar, although the averaged biases are often very different, indicating the homogeneous external field contributions within the small spatial region. In Fig. 1 we show examples of monthly bias time series at NGK (Fig. 1, top) and KAK (Fig. 1, bottom) observatories. Note, that the vertical scales are not the same, due to the large differences among their averaged biases.

In order to search for common features and find possible regional effects, we need to consider a region that is densely covered by geomagnetic observatories. The region between 40 and 70° geomagnetic latitude and between 90 and 120° geomagnetic longitude is considered. In the following we focus on the European observatories only (see the last 16 observatories listed in Table 1) and investigate in detail the temporal evolution of biases. We display the monthly biases over the nine years in form of a color-coded matrix for each component (Fig. 2). The observatory biases (lines of the matrices) are ordered by geomagnetic coordinates, with the northern one at the top. The averaged biases as described before, are subtracted from each time series to study any time dependent contribution on a comparable color-scale. To underline any pattern on short time scales, the color-scale is limited to 20 nT, the stronger trends appearing as changes from dark blue to dark red or vice versa, without information about the real magnitude. Clear semi-annual variations are noticed, with larger extremes that appear mostly around October and November, and around May and June of each year. These variations are especially prominent between 2000 and 2005, the period embracing maximum and very early declining phase of the solar cycle 23. We notice that the peak in fall 2000, and spring peaks in 2003 and 2005 have lower values than other peaks. An extra peak appears in March 2003, also lower than the common ones. In the period corresponding to the late declining phase of solar cycle 23, from 2006 to 2009, the semi-annual variations are highly reduced.

4 Conclusions

When using the observatory data in main field modeling, it is crucial that the crustal biases are accurately determined and thereafter applied to the row data. To study the crustal field temporal evolution over nine years (from 2000 to 2009), we compute the monthly biases at 42 observatories. We analyze both the short and long term bias variations. For all components at each observatory we estimate the magnitude of the constant crustal field contributions.

We observe an annual trend in most of biases series. Generally, these trends lie within the SD of the averaged biases, so no clear evidence that the constant crustal field changed significantly over the studied period is found. The comparison of averaged biases obtained using only November and December monthly values of each year with

MAGSAT and Ørsted based biases shows that they are in good agreement for most observatories, indicating that the crustal field probably does not change over the last 30 years. Similar conclusion is obtained by considering 1979.92 and 1999.92 epochs, as reported by Mandea and Langlais (2002). However, we also note that comparison of biases obtained for individual epochs may not be completely representative, since the external fields do not necessarily peak in the same months for different years, as shown in this study. Moreover, when comparing biases for individual epochs we recommend to take into account that external field pattern may differ from one solar cycle to another (e.g. the solar maximum occurring in 2000 was lower than the maximum in 1980).

Part of the studied period, from 2006 to 2009, embraces the late declining phase of the solar cycle 23 and even the solar minimum. This enables us to investigate the changes in the crustal field related to changes in the long-term induction effects in the electrical conductivity anomalies in the lithosphere, thus changes that are unlikely to be of external origin. This period is characterized by slightly increasing trend in X and decreasing trend in Z. That needs to be investigate in detail and will be the subject of some further work.

Time series of monthly biases exhibit distinct oscillatory pattern in the whole time span, which can be linked to external field contributions. The amplitudes of these variations are remarkably larger in the period 2000–2005 than in 2006–2009. Clear semi-annual variations are observed, with larger extremes that appear mostly around October and November, and around May and June of each year in X, and vice versa in Y and Z. A common external field pattern is found for European monthly biases. The dependence of the bias monthly variations on geomagnetic latitudes is not found for non-European observatories.

We plan to continue this study by investigating a better coverage with geomagnetic observatories over geomagnetic latitudes. A possible improvement would also be to quantify the different magnetic field contributions by applying methods presented in our previous studies (Verbanac et al., 2007a, b), but using monthly biases instead of annual mean biases.

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With the data from new satellite mission SWARM and the above proposed extension of our study, we hope to get a better insight into the temporal evolution of biases, regarding both long term trends and short period variations.

Acknowledgements. The results presented in this paper are based on data collected at magnetic observatories. We thank the observatory staff, INTERMAGNET and WDC Edinburgh for promoting high standards of magnetic observatory practice. The minute and hourly data of all geomagnetic components that we used are available at: http://www.intermagnet.org and http://www.wdc.bgs.ac.uk. We thank Vincent Lesur for providing us with GRIMM3 model spherical harmonic coefficients based on CHAMP data, which we used to estimate the core field contribution at observatory locations. These data can be obtained by request (lesur@gfz-potsdam.de).

References

Bloxham, J. and Gubbins, D.: Geomagnetic field analysis IV, Testing the frozen flux hypothesis, J. Roy. Astron. Soc. Can., 84, 139–152, 1986. 497, 500

Campbell, W. H.: Introduction to Geomagnetic Fields, Cambridge University Press, Cambridge, 2003. 497

Gubbins, D. and Bloxham, J.: Geomagnetic field ananlysis III, Magnetic fields on the core-mantle boundary, J. Roy. Astron. Soc. Can., 80, 695–713, 1985. 497, 500

Jacobs, J. A.: Geomagnetism, vol. 2, Academic Press, London, Orlando, 1987. 497

Langel, R.: The main field, in: Geomagnetism, edited by: Jacobs, J. A., Academic Press, London, 1, Chap. 4, 249–512, 1987. 500

Langel, R. and Hinze, W.: The Magnetic Field of the Earth's Lithosphere: the Satellite Perspective, Cambridge University Press, Cambridge, 1998. 497

Langel, R. A., Estes, R. H. and Mead, G. D.: Some new methods in geomagnetic field modeling applied to the 1960–1980 epoch, J. Geomagn. Geoelectr., 34, 327–349, 1982. 497, 500

Mandea, M. and Langlais, B.: Observatory crustal magnetic biases during MAGSAT and Ørsted satellite missions, Geophys. Res. Lett., 29, 11–15, 2002. 498, 500, 503, 507

Mandea, M. and Thèbault, E.: The Changing Faces of the Earth's Magnetic Field: a Glance at the Magnetic Lithospheric Field, from Local and Regional Scales to a Planetary View, Commission for the Geological Map of the World, Paris, 2007. 497

Merill, R., McElhinny, M. and McFadden, P.: The Magnetic Field of the Earth: Paleomagnetism, the Core, and the Deep Mantle, Academic Press, San Diego, 1998. 497

Sabaka, T., Olsen, N., and Langel, R.: A comprehensive model of the quiet-time, near Earth magnetic field: phase 3, Geophys. J. Int., 151, 32–68, 2002. 497

Verbanac, G., Korte, M., and Mandea, M.: On long-term trends of the European geomagnetic observatory biases, Earth Planets Space, 59, 685–695, 2007a. 498, 500, 501, 503

Verbanac, G., Lühr, H., Rother, M., Korte, M., and Mandea, M.: Contribution of the external field to the observatory annual means and a proposal for their corrections, Earth Planets Space, 59, 251–257, 2007b. 503

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Table 1. Average of the bias over nine years (June 2000 to August 2009) for X, Y and Z components at 42 observatories in nT. The solid line separates the non-European from the European observatories.

Code[a]	Long[b]	Lat[b]	h[c]	X_{avr}	SDx	Y_{avr}	SDy	Z_{avr}	SDz
THL	290.833	77.483	57	−58.33	10.10	98.36	4.29	37.65	24.64
RES	265.105	74.690	30	45.80	13.56	35.35	7.19	103.48	21.31
CBB	254.969	69.123	20	69.45	17.59	−114.45	13.99	102.25	18.08
BLC	263.988	64.318	30	163.70	17.26	−32.42	7.54	−88.35	18.23
BRW	203.380	71.320	12	17.90	19.81	−70.71	8.22	−23.61	18.24
YKC	245.518	62.482	198	−1.02	15.32	−46.95	4.19	−163.35	15.20
FCC	265.912	58.759	15	−121.58	13.95	63.28	3.29	−252.20	13.49
CMO	212.140	64.870	197	0.88	17.14	−5.19	7.65	−1.03	10.84
MEA	246.653	54.616	700	92.31	13.96	15.67	3.72	−133.67	8.18
STJ	307.323	47.595	100	32.08	8.67	44.17	3.26	32.24	6.00
OTT	284.448	45.403	75	122.46	10.14	−133.92	1.58	149.54	7.24
VIC	236.580	48.520	197	16.22	11.41	6.74	2.61	−269.21	8.40
BOU	254.767	40.140	1682	−27.13	11.58	32.18	1.88	−125.36	8.81
FRD	282.633	38.210	69	56.86	10.09	−51.35	1.41	137.90	7.47
NVS	83.230	54.850	130	44.74	11.84	−54.28	2.02	34.63	9.21
KAK	140.186	36.232	36	−14.80	13.01	10.07	1.56	−86.22	4.54
HON	202.000	21.320	4	−185.19	12.97	80.80	3.10	−320.61	3.91
MBO	343.030	14.380	7	100.71	11.54	38.71	1.97	75.91	5.17
ABG	72.872	18.638	7	−99.42	18.81	434.06	7.18	713.92	10.75
GUA	144.870	13.590	140	108.58	13.00	74.54	2.40	45.03	4.39
PPT	210.426	−17.567	357	−922.02	15.29	−1039.73	8.72	−398.55	5.16
GNA	115.947	−31.780	60	−35.50	11.73	−100.83	2.56	96.53	7.35
CZT	51.867	−46.431	155	−761.84	12.66	1092.13	3.77	147.66	6.08
PAF	70.262	−49.353	35	439.90	9.76	−141.86	4.76	−322.27	6.11
DRV	140.007	−66.667	30	−155.60	13.68	−420.01	4.18	−2838.61	19.56
SBA	166.763	−77.850	16	−2204.59	8.93	−970.29	11.05	−3748.76	33.56
LRV	338.300	64.183	5	−289.62	11.28	601.40	3.95	−487.13	11.08
TRO	18.948	69.663	105	30.75	13.14	−393.09	4.04	146.89	16.94
ABK	18.823	68.358	380	6.19	12.42	63.02	3.35	42.95	11.29
LER	358.817	60.138	85	−136.18	8.41	176.22	2.99	57.26	8.55
ESK	356.794	55.314	245	1.09	8.21	−32.52	3.27	−35.81	10.71
VAL	349.750	51.933	14	106.90	8.70	−42.43	2.60	−1.01	8.32
WNG	9.073	53.743	50	43.76	9.38	46.63	2.54	−53.22	8.86
HAD	355.516	50.995	95	−51.70	8.74	18.34	2.62	91.28	7.88
HLP	18.816	54.608	1	37.56	11.23	−163.66	2.85	−85.99	8.59
NGK	12.675	52.072	78	−31.60	9.42	0.99	2.77	−62.28	8.32
DOU	4.599	50.100	225	5.37	9.70	−15.50	2.78	99.60	8.27
BEL	20.789	51.836	173	105.20	10.59	140.15	3.25	324.94	7.72
CLF	2.270	48.020	145	−82.09	9.67	−13.00	2.90	124.78	7.48
HRB	18.190	47.873	120	11.12	9.68	−18.34	2.65	−67.00	7.78
THY	17.893	46.900	187	−28.92	10.66	−10.14	2.75	−40.54	6.46
EBR	0.333	40.957	531.5	169.24	12.30	49.82	5.70	−210.28	7.44

[a] According to the IAGA convention.
[b] Observatory geographic coordinates in degrees.
[c] Observatory altitudes in meters.

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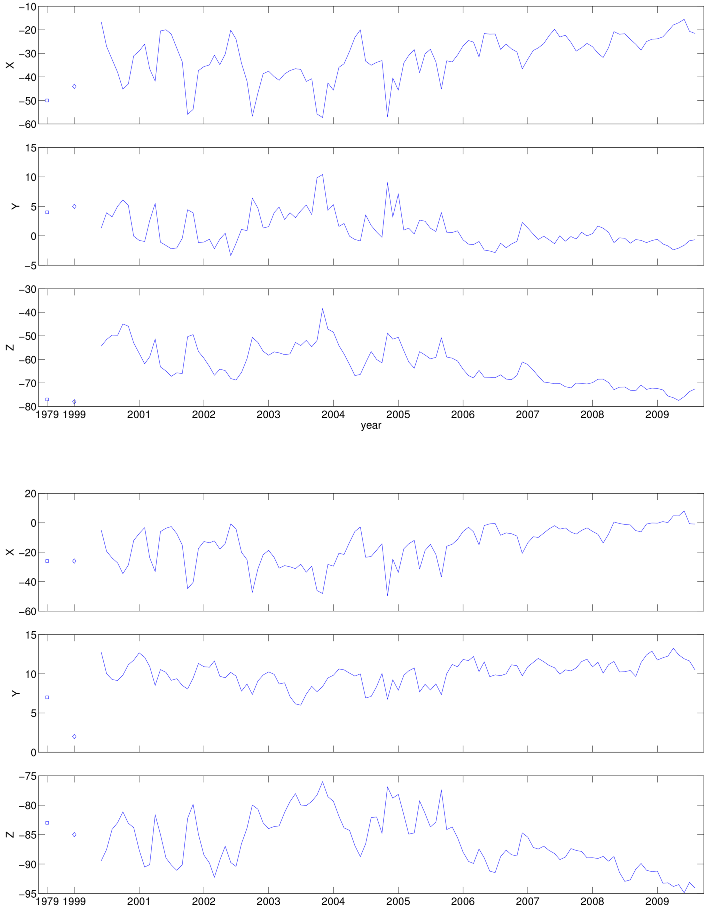

Figure 1. X, Y and Z monthly biases over nine years (June 2000 to August 2009) at NGK (top) and KAK (bottom) observatories in nT. The points at epochs 1979 and 1999 represent MAGSAT and Ørsted based biases computed by Mandea and Langlais (2002).

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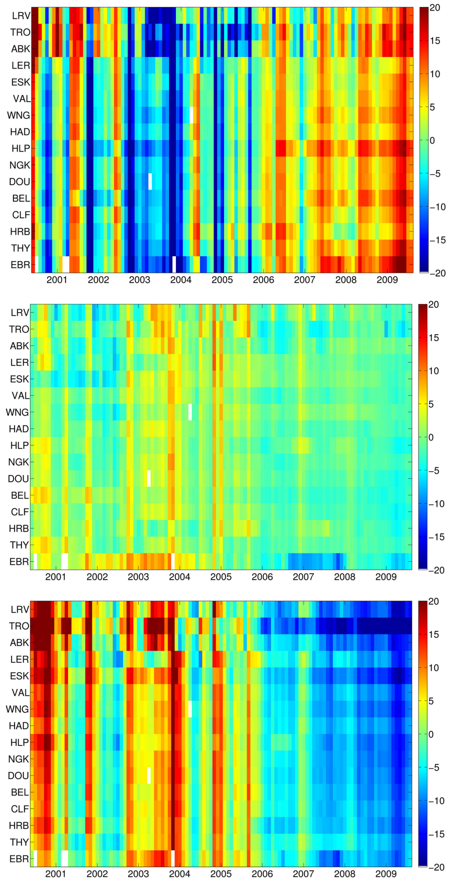

Figure 2. Pictograms of the European X, Y and Z monthly crustal biases over nine years (June 2000 to August 2009) in nT. The observatories (y axes) are ordered by geomagnetic coordinates (northern one at the top).

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