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Geomagnetic repeat station crustal biases and vectorial anomaly maps for Germany

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SUMMARY

Geomagnetic repeat station data of Germany from 1964 to present have been studied to determine their accuracy and crustal biases. Like the data from geomagnetic observatories, repeat station data contain contributions from the regional and local crustal field, but their spatial density is by far not high enough to resolve such anomalies. Knowing this crustal bias, therefore, is important in using repeat station data to map or model the main field. To confirm the results obtained by using a global geomagnetic field model we constructed regional lithospheric field models using additional information from satellite and aeromagnetic data. The compatibility of the different data types is good and we present vectorial anomaly maps for Germany with a spatial resolution of approximately 37 km, which could be useful for future geological interpretation of magnetic anomalies.

The anomalies contributing to the repeat station bias, however, can be of smaller scale and their amplitudes range up to absolute values of 177 nT in the north (X), 106 nT in the east (Y) and 176 nT in the vertical (Z) component. Average uncertainty estimates in the order of 5, 8 and 5 nT in X, Y and Z, respectively, are obtained from comparisons to a global model. The estimates, however, vary a lot between stations and components. The uncertainties should mostly result from measurement errors, insufficient elimination of external field contributions or relocations of stations which had been regarded as insignificant. There might also be a small contribution from insufficient description of secular variation in the global model used.

Key words: geomagnetic repeat station survey, magnetic anomalies, regional magnetic field modelling.

1 INTRODUCTION

Geomagnetic repeat stations are well-defined locations where magnetic field measurements are taken once a year to once every few years. Repeat station networks exist in several countries and the measurements traditionally complement observatory data to provide better global data coverage in areas with few observatories and for detailed regional mapping of the core field and its secular variation (Newitt *et al.* 1996). Recently, a new application for repeat station data has been presented in the determination of vectorial crustal magnetic anomaly maps with R-SCHA, the revised spherical cap harmonic analysis (Thébault *et al.* 2006b). Based on the spherical cap harmonic analysis (SCHA) as pioneered by Haines (1985), this new method is capable of combining ground, aeromagnetic and satellite data through an improved altitude-dependence in the models. It takes full advantage of the complementary information contained in the different data types: Observatory and repeat station data provide full vector information, but not the spatial resolution to resolve local crustal magnetic anomalies. Aeromagnetic data have the best available spatial resolution, but only for field intensity, without directional information. Moreover, individual aeromagnetic surveys in general cover small regions, and even larger compilations which are stitched together mostly lack spatial long-wavelength information, that is anomalies caused by very large or deep sources. This information is provided by satellite data, which also offer the full vector description but due to the altitude above the surface once again lack the detailed spatial resolution of anomalies caused by small and shallow bodies. A R-SCHA model gives a full 3-D description of the lithospheric vector anomaly field from ground to satellite altitude.

Whatever the purpose of repeat station data, a high accuracy is required for them to contain reliable information about the internal field additional to that contained in observatory data (see Newitt *et al.* 1996). Apart from the measurement practice itself, the careful correction for short-period external variations plays a significant role. Even magnetically quiet time daily variations and moderately disturbed night time variations can reach the same orders of magnitude as annual secular variation and have to be corrected for. At geomagnetic observatories with continuous recordings it is commonly assumed that annual mean values, that is, the means of the

*Now at: Institut de Physique du Globe de Paris, 4, place jussieu, Paris 75252, France. E-mail: EThebault@ipgp.jussieu.fr recordings from a whole year, are a reasonable representation of the core (and crustal) field and all external variations have averaged out. However, it is also well-known that this is not completely true (e.g. Courtillot and Mouël 1976; Schmucker 1991; Verbanac *et al.* 2006) and a simple empirical correction in the frame of this study will be discussed further in Section 2.2.

At repeat stations, the measurements are comparable to the discrete absolute measurements at geomagnetic observatories, but continuous variation recordings for a whole year are not available. Corrections for any external field variations are commonly obtained either by using the variation recordings of the nearest observatory or of a local variometer (see also Newitt *et al.* 1996). In the first case it has to be assumed that the variations at the repeat station and the observatory are exactly the same. Any component value $C(t_m)$ measured at a repeat station at the time t_m can be reduced directly to an 'annual mean' value $\bar{C}$ at the repeat station by means of

$$\bar{C} = \bar{C_O} + [C(t_m) - C_O(t_m)]. \quad (1)$$

Here, $C_O(t_m)$ is the equivalent value measured at the same time at the observatory O and $\bar{C_O}$ is the observatory annual mean value. Each individual result obtained this way will directly contain the difference in variations as error, which might or might not average out with multiple measurements. In the second case, a three-component magnetometer (variometer) is set up near the station to record the field variations during some time interval including the time of measurements at the station and preferably also magnetically quiet periods. Absolute variation values for the duration of variometer recordings are obtained by calibration with the discrete measurements at the repeat station, just as at a geomagnetic observatory. The reduction to 'annual means' can then be done by determining the difference $C(t) - C_O(t)$ in eq. (1) from quiet time values or a longer time average, that is, t can now mean a whole time interval up to the duration of the local variometer recordings. Differences in geomagnetic variations between the nearest observatory and a repeat station can be significant, in particular, if the observatory is far away, geomagnetic activity is high or lithospheric conductivity differs. The use of a local variometer gives a more robust estimate of the internal field difference and thus of the resulting 'annual mean' at the repeat station. However, mostly repeat station data are published without uncertainty estimates.

The aim of this study is three-fold: First, to assess and discuss the quality of the German repeat station data and the improvements from the recently introduced method of using local variometers. Second, we will present vectorial geomagnetic anomaly maps of Germany, based on simultaneous R-SCHA modelling of observatory, repeat station, aeromagnetic and satellite data. This detailed description of not only the intensity, but also the directional distribution of magnetic crustal anomalies could offer valuable information for future geological studies. The compatibility of different data types in the modelling is used here to support the discussion of repeat station data quality. Third, the model provides well confirmed information on crustal biases at the geomagnetic repeat stations. The term 'crustal bias' has been introduced by Langel *et al.* (1982) to describe the lithospheric field contribution at geomagnetic observatory locations. It is impossible to separate this and the core field contribution in data from individual locations. The crustal bias can only be determined by subtraction of a core field model or by co-estimation in field modelling. It is useful to know the crustal bias at any measurement location in order to eliminate it from the data for core field studies, and to prevent distortions from local anomalies in regional mapping of repeat station results by interpolation.

Table 1. Temporal distribution of repeat station data used in this study.

Epoch	Former GDR	Former W. Germany
1965.0		x
1982.5		x
1985.5	x	
1986.5	x	
1987.5	x	
1988.5	x	
	Germany	
1992.5	x	
1996.5	x	
1999.5/2000.5	x	
2001.5/2002.5	x	
2003.5	x	

2 DATA

2.1 Repeat station data

Germany does not have a long tradition of true repeat station surveys with less than 5 yr repeat intervals, but several of the currently used stations have been established as early as 1934/1935 (Bock *et al.* 1948). True repeat station surveys over all of current Germany started with a survey of the reunified country, reduced to 1992.5 (Beblo *et al.* 1995; Schulz *et al.* 1997). This survey was carried out on the network of repeat stations in the former GDR, established in 1985 and surveyed annually to bi-annually up to 1988, and a subset of stations used in occasional ground vector surveys of former Western Germany. The data from the two latest of these ground vector surveys are reduced to 1965.0 (Voppel & Wienert 1974) and 1982.5 (Schulz & Beblo 1991), respectively.

A survey reduced to 1996.5 was the first in a series of regular repeat station re-occupations. The following surveys were carried out in a way that half the network was visited per year. To minimize data reduction errors from secular variation, the data are reduced to the middle of the year in which the measurements were carried out. Results exist for 1999.5/2000.5 (Korte & Fredow 2001) and 2001.5/2002.5. In 2003, the initiative to homogenize all the European repeat station surveys, now named Magnetic Network of Europe (MagNetE), started (Korte & Mandea 2003). The resulting agreement was to carry out common repeat station measurements on the complete networks or evenly distributed subsets of stations in all countries bi-annually, starting in 2004. Consequently, the survey already planned for Germany at that time for 2003 was extended to as many stations as possible, yielding results reduced to 2003.5 for most of the stations. Further surveys were carried out in 2004 and 2006. Table 1 gives an overview of the temporal distribution of the data used in this study.

A portable three-component variometer for improved data reduction (Newitt *et al.* 1996) was used for the first time in 1999. The effort of putting up the variometer for several days to include magnetically quiet conditions at every single one of over 50 stations was not feasible and we had to compromise and use several central variometer stations instead (Korte & Fredow 2001). This yields a network of first and second order stations: on a sparse network of first order stations the external variations are determined excellently by the near-by variometer for optimal data reduction. The density of stations is increased by second order stations where the external variations can still be accounted for to a high level by the variometer no further than 150 km away. New experiences from the use of this variometer and problems from technical disturbances at a few stations led to some changes in both repeat station and variometer network between 1999 and 2004.

In order to reduce data uncertainties we want to use as many results from individual stations as possible. At the same time, we need a good reference model, describing accurately the core field and its secular variation to study crustal biases and data accuracy. The Comprehensive Model CM4 (Sabaka *et al.* 2004), spanning the interval 1960–2002 using mathematical functions which are continuous in time, is currently the most suitable model for that purpose. The model will output extrapolated values outside its range of valitidy, but the quality of the secular variation extrapolation deteriorates quickly. Compromising between the desire to use as many of the recent high-quality repeat station results as possible, but evading the influence of inappropriate secular variation extrapolation in the model, we included the 2003.5 data in this study but no more recent data. Moreover, we only included stations which were surveyed more than twice and have been part of the network after 1999. This results in a data set from 48 repeat stations plus the three observatories Niemegk, Wingst and Fürstenfeldbruck (Fig. 1). In summary, the data from the 48 repeat stations (*cf*. Table 2) come from 3 to 11 occupations in the years listed in Table 1. All these data are available from the WDC Edinburgh at http://www.geomag.bgs.ac.uk/gifs/surveydata.html.

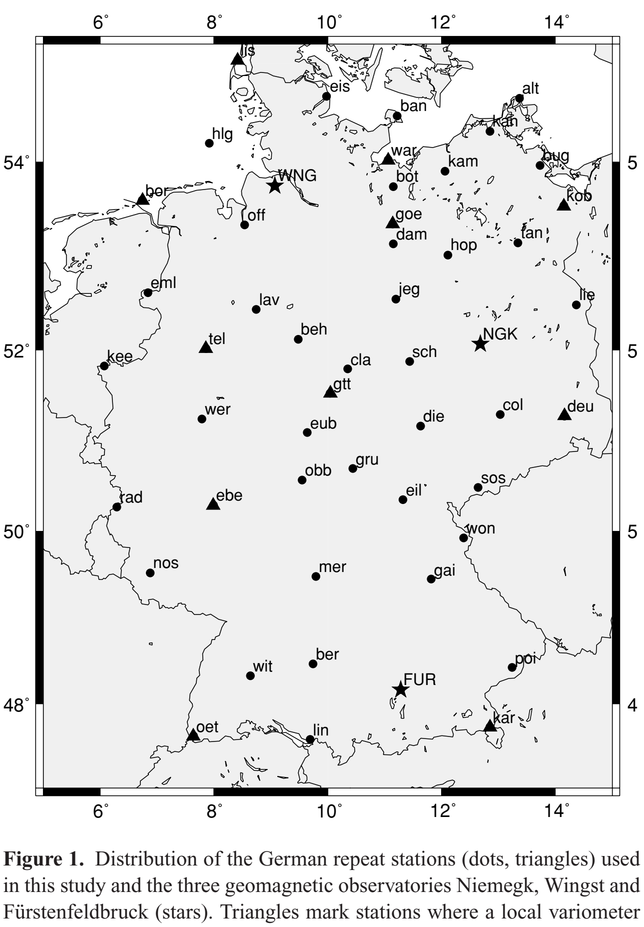

Figure 1. Distribution of the German repeat stations (dots, triangles) used in this study and the three geomagnetic observatories Niemegk, Wingst and Fürstenfeldbruck (stars). Triangles mark stations where a local variometer has been used since 1999.

Table 2. Location of repeat stations with number of measurements (X) in the time interval 1960–2004 and name abbreviation used in this work. Sites where local variometers were used since 1999 are marked in bold face font.

Lat.	Long.	Alt. (m)	X	Abbr.	Name
54.652	13.367	20	7	alt	Altenkirchen
54.471	11.225	10	6	ban	Bannesdorf
52.123	9.477	153	3	beh	Behrensen
48.471	9.743	743	6	ber	Berghuelen
53.596	6.744	2	5	**bor**	**Borkum**
53.745	11.152	58	8	bot	Botelsdorf
53.962	13.730	24	8	bug	Buggow
51.795	10.351	601	6	cla	Clausthal
51.298	13.025	200	3	col	Collm
53.137	11.154	13	4	dam	Damnatz
51.285	14.163	160	10	**deu**	**Deutschbaselitz**
51.173	11.630	290	9	die	Dietrichsroda
50.289	7.986	364	2	**ebe**	**Ebertshausen**
50.348	11.324	442	4	eil	Eila
54.669	9.984	23	5	eis	Eiskeller
52.623	6.838	15	7	eml	Emlichheim
51.097	9.638	334	4	eub	Eubach
49.445	11.817	418	6	gai	Gailoh
53.350	11.142	13	9	**goe**	**Goesslow**
51.531	10.045	289	7	**gtt**	**Goettingen**
50.698	10.442	460	9	gru	Grumbach
54.185	7.916	2	4	hlg	Helgoland
53.025	12.107	65	9	hop	Hoppenrade
52.555	11.197	70	9	jeg	Jeggau
53.900	12.065	30	9	kam	Kambs
47.727	12.853	550	7	**kar**	**Karlstein**
54.312	12.847	10	10	kan	Karniner Holz
51.829	6.071	12	7	kee	Keeken
53.537	14.147	10	8	**kob**	**Koblentz**
52.438	8.743	48	7	lav	Lavelsloh
52.490	14.368	50	4	lie	Lietzen Vorwerk
47.578	9.691	493	7	lin	Lindau
55.036	8.417	11	5	**lis**	**List**
49.480	9.795	337	6	mer	Bad Mergentheim
49.526	6.879	309	7	nos	Noswendel
50.574	9.548	303	6	obb	Oberbimbach
47.621	7.638	454	8	**oet**	**Oetlingen**
53.337	8.541	0	3	off	Offenwarden
48.426	13.240	427	7	poi	Poigham
50.270	6.295	575	7	rad	Radscheid
51.877	11.438	140	5	sch	Schneidlingen
50.488	12.643	690	11	sos	Sosa
53.152	13.342	62	9	tan	Tangersdorf
52.018	7.855	75	6	**tel**	**Telgte**
54.015	11.064	13	13	**war**	**Warnkenhagen**
51.252	7.791	375	7	wer	Werdohl
48.328	8.636	554	6	wit	Wittershausen
49.919	12.386	580	6	won	Wondreb

2.2 External variation correction

It is well known that the external variation influence and their induced counterparts do not average out completely in observatory annual means, and repeat station 'annual means' consequently must be affected similarly. To address the question of this influence we compared the annual means of the three German observatories from 1965.5 to 2003.5 to CM4 model predictions. In this model, apart from the main field, the lithospheric field up to spherical harmonic degree and order 65 is included as well as several external sources and their induced effects. The description of the external sources is based on magnetically quiet conditions and modulated with the

Table 3. Average offsets (a0, nT) between observatory data and CM4 internal field predictions and slope (a1, nT yr^{-1}) of linear regression line.

Obs	*X* a0	*X* a1	*Y* a0	*Y* a1	*Z* a0	*Z* a1
WNG	−9.0	−0.0168	38.8	0.1143	−42.9	0.0103
NGK	−60.3	−0.0933	16.1	0.1128	7.5	−0.1097
FUR	−27.9	−0.0142	7.5	0.1397	19.6	0.0263

Dst index of magnetospheric ring current activity and the F10.7 solar flux index. However, these modulations are insufficient to predict the net effect of external and induced magnetic fields in annual means averaged from minute values (Verbanac *et al.* 2006). As all repeat station annual means are influenced by the net annual external fields exactly like the observatory annual means they are based on, we chose an empirical approach to correct for those influences based on the homogeneity of them over a small area such as Germany.

We compare the observatory data to CM4 predictions of internal field up to degree and order 65 (main and lithospheric), but not the external field contributions. As we do not expect subannual variations in secular variation due to the filtering effect of the mantle we obtained 'annual mean' model predictions in this case simply by averaging 10 prediction values evenly distributed throughout 1 yr. It is obvious that there are systematic deviations from different sources. Constant offsets originate in local crustal anomalies of shorter wavelength than represented in CM4. Short period (years to solar cycle period) variations must be assumed to be mainly of external origin. To separate the residual external influence C_{res} for each component, we first subtracted the constant average values from the individual time-series, and also a best fit linear trend (Table 3), which we suppose to originate in locally slightly insufficient secular variation description in the subtracted CM4 model and not in any external field influence. For the three German observatories of Wingst, Niemegk and Fürstenfeldbruck the remaining deviations are of similar amplitude of up to ±10 nT in *X* and ±5 nT in *Y* and *Z* (Fig. 2). Note that from mid 2002 on we are in the extrapolation range of CM4, which should be regarded with caution like any extrapolation. For *Y* and *Z* the difference between data and model predictions for 2003.5 is slightly larger than on average.

The deviation values of the three well-distributed observatories are very similar (Fig. 2), confirming that the annually averaged effects of external fields and their induced counterparts are reasonably homogeneous over the (comparatively small) region of Germany. It is important to note, however, that particularly for the induced parts the homogeneity is only true for long-term averages. Significant differences in short-term variations due to regional or local conductivity anomalies exist—thus the need for local variometers at the repeat stations. We assume the averages of the three time-series to be good templates for external and induced influences on all the annual means. Subtracting the template values from the individual observatories time-series confirms the assumption: the scatter

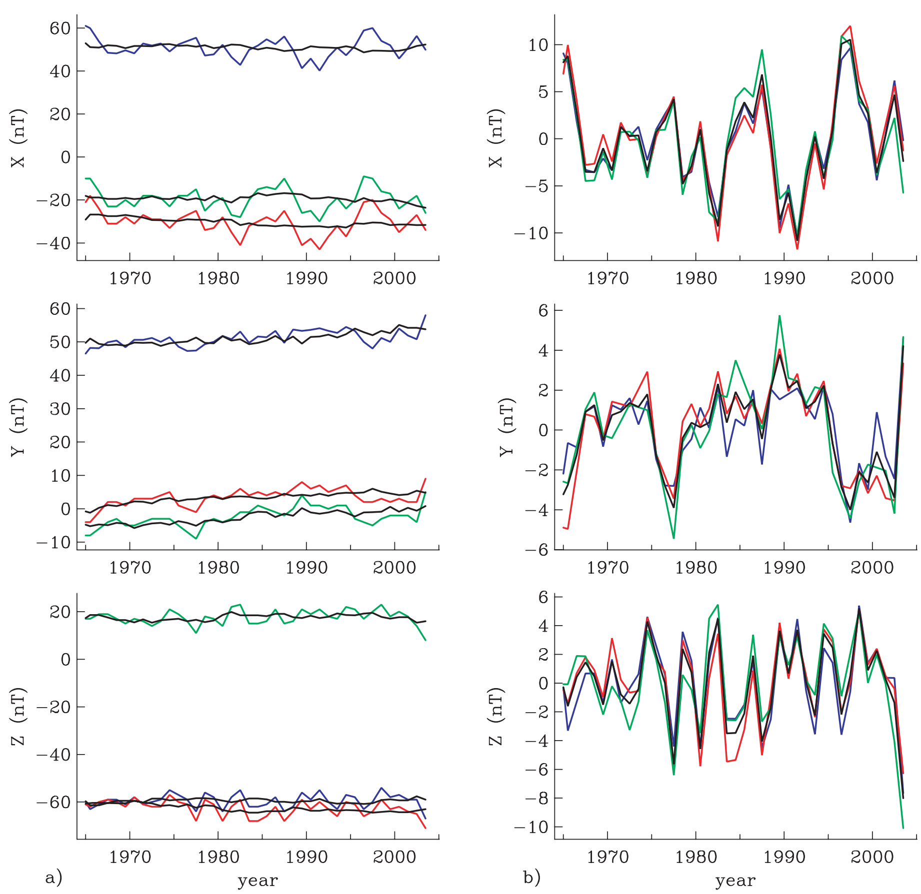

Figure 2. Variations of geomagnetic north (*X*), east (*Y*) and vertical (*Z*) component of the observatories Niemegk (NGK, red), Wingst (WNG, green) and Fürstenfeldbruck (FUR, blue) after subtraction of CM4 core and lithospheric field predictions (a). Constant offsets and linear trends have been subtracted in (b), where the black line is the average of the three time-series, which is used as template for elimination of external field influence. The black lines in (a) show the observatory data after subtraction of CM4 core and lithospheric field and this external influence template.

Table 4. Standard deviation between observatory data and CM4 internal field predictions in nT before and after external influence correction.

Obs	σX	σY	σZ	σX_{corr}	σY_{corr}	σZ_{corr}
WNG	4.72	2.44	2.87	1.10	1.72	0.89
NGK	5.64	2.80	3.34	1.82	1.67	1.55
FUR	5.39	3.06	3.15	1.47	1.93	1.29

Table 5. Scatter reduction $\delta\ \sigma$ and scatter σ with minimum and maximum values for individual stations after external influence correction of repeat station data in nT.

Comp.	Avg. $\delta\ \sigma$	min $\delta\ \sigma$	max $\delta\ \sigma$	Avg. σ	min σ	max σ
X	3.0	−1.4	6.4	4.7	0.16	20.22
Y	0.3	−2.6	4.5	8.3	1.16	17.82
Z	1.5	−2.0	5.9	4.5	0.79	19.87

(standard deviation) about the mean is reduced by 3.8 nT in X, 1.0 nT in Y and 1.9 nT in Z by subtraction of the template (see Table 4). The average offsets themselves do not change. The template values for the respective epochs can be subtracted from repeat station annual means for correction for external influences to the same accuracy.

2.3 Crustal contribution in repeat station data

To determine the crustal contribution in the repeat station data as input for the R-SCHA modelling and to estimate the crustal biases we subtracted the CM4 internal field predictions up to spherical harmonic degree and order 14 from the data and calculated the average anomaly value at each station from the 3 to 11 results distributed unevenly over time.

The subtraction of the templates for external field correction reduced the scatter by 3.0 nT in X, 0.3 nT in Y and 1.5 nT in Z on average (Table 5). Although these average reductions are only slightly smaller than those at the observatories, there are a few individual repeat stations where the scatter increases by the correction (Fig. 3). This reflects the larger uncertainties in the repeat station

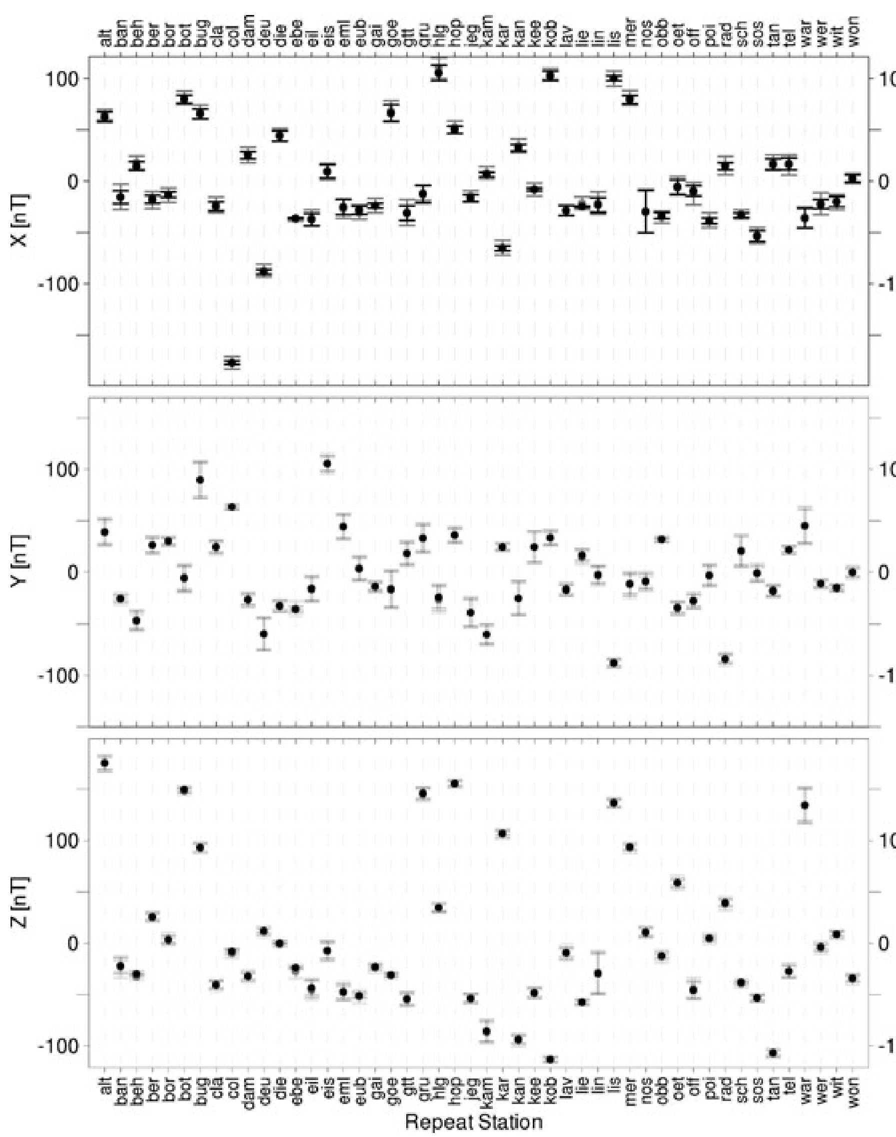

Figure 3. Average station bias, that is data with CM4 core field subtracted, with standard deviation before (grey) and after (black) external field correction. North (X), east (Y) and vertical (Z) component.

data and there is no correlation of improvement by the correction to location, neither latitude nor longitude. Moreover, in contrast to the observatory case, for the repeat stations the average offsets to CM4 predictions are sometimes influenced by the correction due to the uneven temporal distribution of these time-series. Average offset changes of up to 4.7 nT in X, 1.2 nT in Y and 1.8 nT in Z occur. Table 6 gives the final crustal anomaly values together with the standard deviations. The scatter remains large in a few cases even after the external influence correction. It can be seen as uncertainty estimate on the repeat station data for the crustal field modelling. Remember, however, that at some stations these statistics are done for no more than three individual annual mean values. Details about individual stations and repeat station data quality will be discussed together with the repeat station biases in Section 4.

Table 6. Repeat station biases with standard deviation for the geomagnetic components in nT.

X	σX	Y	σY	Z	σZ	Station
62.76	5.03	39.21	12.91	175.58	6.99	alt
−15.58	6.28	−25.09	2.63	−22.00	6.72	ban
14.69	4.23	−46.27	9.44	−29.72	1.67	beh
−17.64	3.84	26.23	7.37	25.83	3.06	ber
−13.10	2.67	30.35	3.80	3.35	3.34	bor
79.88	3.88	−6.11	12.20	149.89	2.42	bot
65.68	4.85	89.82	17.40	93.22	4.50	bug
−24.39	4.34	24.58	5.32	−40.32	3.32	cla
−176.62	1.78	63.59	2.17	−7.83	2.05	col
25.36	3.36	−25.96	6.10	−32.25	3.36	dam
−88.27	2.21	−59.62	15.54	12.23	2.71	deu
44.18	4.93	−32.29	4.91	0.12	1.58	die
−36.10	0.39	−35.58	2.21	−23.83	0.79	ebe
−37.33	6.03	−15.95	11.85	−43.30	8.08	eil
9.54	6.50	105.58	6.93	−7.06	8.29	eis
−25.09	7.44	44.21	11.71	−47.67	6.78	eml
−27.88	4.31	3.02	11.17	−51.02	2.20	eub
−23.99	2.35	−13.90	3.79	−22.88	1.95	gai
66.29	8.20	−16.31	17.64	−30.68	1.58	goe
−30.95	7.20	18.12	10.87	−54.18	5.82	gtt
−12.57	8.69	32.99	13.78	146.18	5.51	gru
105.49	7.57	−23.78	11.10	34.89	3.77	hlg
50.29	3.44	35.93	7.26	155.77	2.96	hop
−16.69	3.37	−38.74	14.05	−53.46	4.01	jeg
6.55	2.13	−60.12	9.68	−85.51	10.72	kam
−65.43	2.54	24.55	3.17	107.02	2.47	kar
32.63	3.16	−24.91	15.68	−93.70	3.96	kan
−8.01	1.39	24.35	14.86	−48.43	4.66	kee
102.60	4.62	33.37	7.17	-113.15	2.46	kob
−28.55	4.95	−16.64	5.01	−9.28	4.55	lav
−24.76	0.51	16.50	5.46	−57.35	1.92	lie
−23.10	7.05	−2.53	8.39	−29.49	19.97	lin
100.46	2.41	−87.65	3.61	136.55	3.70	lis
79.54	4.05	−11.34	9.58	93.87	2.57	mer
−29.75	20.64	−8.95	7.94	10.94	4.11	nos
−33.54	3.11	31.85	1.52	−12.30	2.41	obb
−5.78	7.20	−33.95	5.70	58.81	3.26	oet
−9.38	4.99	−27.21	7.05	−45.79	8.10	off
−38.75	2.65	−3.13	9.66	4.98	1.96	poi
14.53	3.45	−83.70	3.85	39.42	2.99	rad
−33.21	2.26	20.63	14.47	−37.77	1.42	sch
−53.50	5.30	−1.15	7.27	−53.09	3.11	sos
16.29	5.54	−17.91	5.04	−106.68	2.99	tan
16.88	5.90	21.67	3.55	−27.17	6.42	tel
−36.03	9.44	45.02	16.48	134.60	16.06	war
−22.38	4.50	−11.25	4.09	−3.72	2.89	wer
−19.88	4.96	−15.04	2.10	8.95	2.40	wit
2.76	3.63	−0.21	3.92	−34.03	2.49	won

2.4 Aeromagnetic data

German aeromagnetic surveys were carried out at different altitudes and epochs, recorded in different coordinate systems and acquired along different profile spacings (Wonik *et al.* 2001). Independent data sets have different quality due to instrumentation changes and data processing. Stitching them together will, therefore, produce inconsistent large-scale patterns. Wonik *et al.* (2001) published a magnetic map for northern, western and eastern Europe at a scale of 1:20 400 000. They compiled the available data sets over Europe, upward/downward continued them to 3 km altitude and reduced them to the year 1980.0 using a regional secular variation description based on European observatory and repeat station data. Finally, the DGRF 1980 core field model was subtracted. Here, we consider this compiled data set over Germany and neighbouring countries because it yields an evenly distributed set of data near the Earth's surface and assumes a fairly reliable large-wavelength content throughout the region of interest. The resolution of the compilation is significantly higher than global crustal field models based on satellite data. In order to remain consistent with the repeat station data reduction, first the DGRF 1980 model was added and then the CM4 model up to degree and order 14 subtracted from the aeromagnetic intensities. In combining the aeromagnetic anomaly data with the more recent repeat station and satellite data, we implicitly assume that the secular variation contributions from degrees higher than 14 are negligible compared to data errors. In general, we should not ignore the possible bias introduced by the reduction method. However, considering the somewhat limited accuracy of repeat station data and an estimated uncertainty of ± 10 nT over Germany in the aeromagnetic data (Wonik *et al.* 2001), together with the resolution of our modelling the assumption should be justified. In this study, we consider 23 376 anomaly intensity data distributed homogeneously at 3 km altitude above the sea level within our modelling region (see Section 3.1).

Note, however, that differences exist between the data compilation for the European Geotraverse (Wonik *et al.* 1992) and the European compilation used here. In a preliminary study we used the Geotraverse grid over Germany, but these data did not cover the whole area required by the modelling method and could not ascertain the robustness of the model. Despite the fact that Wonik *et al.* (2001) used the same data set for their final compilation, we found differences and inconsistencies in the European data. The first problem was an apparent shift in magnetic anomalies compared with the geology and previous magnetic maps over the region (Wonik & Hahn 1989). This was found to result from an error in the coordinate origin of the European compilation. The consistent origin was found empirically after several attempts and comparison. The second difference, which rendered the first one even more difficult to solve, is that the European compilation has a lower resolution than the original Geotraverse grid. While we determined a resolution of about 10 km in the Geotraverse data, we notice a fall-off in the spectral representation of the European data at about 25–30 km wavelength. We may, therefore, expect substantial differences between the model using this data set and ground data since small-scale anomalies are not well represented in the European aeromagnetic compilation.

2.5 Satellite data

The Earth-orbiting satellite CHAMP was launched in 2000 and has a low, circular and near-polar orbit. Because of the lower orbit compared to other current magnetic satellite missions and its vector data quality, we use data exclusively from this mission. The orbit characteristics are suitable for crustal field detection and the experience gained over the 5 yr of CHAMP activity has resulted in a series of effective adjustments and corrections essential in its data processing. Corrected data are now of high quality and field models have become increasingly robust and reliable (Maus *et al.* 2006). Almost 5 yr of selected CHAMP scalar and vector data from 2000 August to 2005 January were provided to us by S. Maus (personal communication, 2005) and are used in the present study. The data set includes only the least disturbed satellite tracks from local time sector 0:00 to 5:00 h LT with $Kp \leq 2$ and a maximum of $Kp = 2.5$ for the previous 3 hr. Data are corrected for star camera misalignment. A secular variation model is estimated from the data and the POMME 2.5 core field model (http://www.gfz-potsdam.de/pb2/pb23/SatMag/pomme2.html) up to degree and order 14 is subtracted, as well as an external field estimation. We could not use the CM4 model used with the other data types for the core field subtraction here because it is not valid up to 2005. The POMME model, on the other hand, is not valid before 2000 and thus could not be used on the repeat station and aeromagnetic data. Other corrections like polar electrojet or tidal corrections are applied to the satellite data, but influence mainly oceanic or polar regions. Details about the data pre-processing are described in Maus *et al.* (2006). The selection and the reduction procedures yield 6613 scalar data and 2613 vector data distributed between 350 and 480 km altitude over the region of interest.

3 CRUSTAL ANOMALY MODELS AND REPEAT STATION BIASES

3.1 Modelling method

We use the R-SCHA procedure described in Thébault *et al.* (2006a). In a source-free region delimited by two spheres of minimal and maximal radial distances $r = a$ and b and a cone C with half-angle θ_0, the magnetic field may be expressed by means of basis functions solving the Laplace equation $\nabla^2 V = 0$. The Laplace equation may further be associated with boundary conditions on each surface and the overall solution is (Thébault *et al.* 2006b):

$$\begin{aligned} V(r,\theta,\varphi) = & \\ & a \sum_{k\geq 1}\sum_{m\geq 0}\left(\frac{a}{r}\right)^{n_k+1}\left[G_{n_k}^{i,m}\cos(m\varphi) + H_{n_k}^{i,m}\sin(m\varphi)\right]P_{n_k}^m(\theta) \\ & + a\sum_{l\geq 1}\sum_{m\geq 0}\left(\frac{r}{a}\right)^{n_l}\left[G_{n_l}^{e,m}\cos(m\varphi) + H_{n_l}^{e,m}\sin(m\varphi)\right]P_{n_l}^m(\theta) \\ & + a\sum_{p\geq 0}\sum_{m\geq 0}R_p(r)\left[G_p^m\cos(m\varphi) + H_p^m\sin(m\varphi)\right]K_p^m(\theta) \end{aligned} \quad (2)$$

with $P_{n_k}^m$ the associated Schmidt semi-normalised Legendre functions of integer order m and generally real degrees n_k, $K_p^m(\theta)$ the conical or Mehler functions and $R_p(r)$ a radial function comparable to Fourier series and dependent on the minimal and maximal radii a and b. The parameters $\{G_p^m, H_p^m\}$, $\{G_{n_k}^{m,i}, H_{n_k}^{m,i}\}$, $\{G_{n_k}^{m,e}, H_{n_k}^{m,e}\}$ are the unknown coefficients to be determined by an inverse method.

Taking the maximum and minimum altitude in our data, we set $a = 6361.2$ and $b = 6871.2$. Here, the cone is centered on the geocentric latitude $\Theta = 51^\circ$ and the longitude $\Phi = 10^\circ$ and has an half-angle $\theta_0 = 5^\circ$. The choice of θ_0 has a direct influence on the n_k values and, together with the maximum degree of the expansion, determines the minimum wavelengths representation (Haines 1985; Thébault *et al.* 2006b).

As already mentioned, we consider the residual field, which is the difference between the magnetic field measurements $\mathbf{B}_m$, or its intensity F_m, and a core field model $\mathbf{B_c}$ with intensity F_c such that:

$$\delta\mathbf{B}(r,\theta,\varphi) = \mathbf{B}_m(r,\theta,\varphi,t) - \mathbf{B}_c(r,\theta,\varphi,t) \quad (3)$$

and

$$\delta F(r,\theta,\varphi) = F_m(r,\theta,\varphi,t) - F_c(r,\theta,\varphi,t). \quad (4)$$

Setting $\delta\mathbf{B} = -\nabla V$ and using eq. (3) provides the complete vector form for the magnetic lithospheric field (see Thébault *et al.* 2006a).

Since the measurements $\mathbf{d}$ are a combination of scalar and vector data, the model parameters $\mathbf{g}$ are estimated using the usual damped least-squares iterative process:

$$\mathbf{g}_{i+1} = \mathbf{g}_i + \left[\alpha\mathbf{E} + \left(\mathbf{A}^T\mathbf{A}\right)_i\right]^{-1}\left\{\mathbf{A}_i^T\left[\mathbf{d} - f(\mathbf{g}_i)\right] - \alpha\mathbf{E}\mathbf{g}_i\right\} \quad (5)$$

with $\mathbf{A}$ the matrix of Frechet derivative such that $\mathbf{A}_{ij} = \frac{\partial f_i(\mathbf{g})}{\partial \mathbf{g}_j}$, $\mathbf{E}$ the norm of the magnetic field shaped into a diagonal form, and α the damping parameter giving the best trade-off between fit to the data and model smoothness.

The inverse problem is solved by singular value decomposition and is regularized using the minimum energy constraint. In theory, the series in eq. (3) are infinite but in practice maximum truncation indices have to be defined according to data distribution and availability at different surfaces. Near the Earth, the 5 km intensity grid is nearly homogeneous and we set $K_{\max} = 30$. This gives a maximum spatial representation of 37 km at the ground; using a higher truncation index is too demanding in terms of computer resources. Satellite data do not detect wavelengths smaller than approximately 400 km and a high degree expansion is unnecessary for them. We set $L_{\max} = 10$, which corresponds, roughly, to a maximum spatial representation of 270 km at the Earth. Similarly, the Mehler basis function $K_p^m(\theta)$ determine the model behaviour with respect to upward/downward continuation but also near the cap's edges (Thébault *et al.* 2006a). The general distribution with altitude is poor and a data gap of nearly 350 km exists between the highest ground data and the lowest satellite data. Setting $P_{\max} = 10$ represents a good trade-off between the data resolution, the proper field representation with altitude, and the conditioning of the inverse problem. Overall, we co-estimate 1166 local parameters to describe the data. The conditioning can be further improved by the parameter α in (5), which may be split into α_L and α_M, respectively, for the Legendre and the Mehler basis functions.

3.2 Boundary effects and the importance of ground vector data

Boundary effects, related to the well-known Gibbs phenomenon, always distort the magnetic field prediction near the lateral boundaries. This is inherent to any regional modelling and has always been a major issue in the use of spherical cap harmonics. Using the full set of basis functions considerably improves the problem but does not fully rectify it. Using synthetic data calculated from the CM4 crustal field model at the locations of our repeat station data we first qualitatively checked that the utilized spherical cap harmonic expansion degree was sufficient to force edge effects to lie within 4.7° and 5° of colatitude (in the cap's reference frame). The Gibbs effect in this region is estimated to represent less than 2 per cent of the magnetic anomaly field intensity in this case.

Our purpose is to reliably estimate the full anomaly field at ground level with mainly scalar aeromagnetic data. We performed two synthetic inversions using the same modelling parameters, first with and second without repeat station data. The correlation between the two models is 0.99 but we notice an important disparity between Legendre (P_{nk}^{m}) and Mehler coefficients (K_{p}^{m}). Legendre parameters have a correlation of 0.99. In contrast, a lower correlation between the Mehler coefficients (0.97) indicates differences in behaviour of the two models with altitude and near the cap edges, as these coefficients contribute mainly in these regions. Both models are equivalent when comparing anomaly intensities but the change is significant for the vector field and its altitude variation. Predictions at altitudes where no data are available correlate better with the input synthetic data (0.95 at 100 km, 0.92 at 200 km, and 0.90 at 300 km) if ground vector measurements are added. In the absence of synthetic repeat station values, the correlation coefficient drops to 0.8 on average with a maximum discrepancy near the cap's edges. Repeat station data are measured at the ground level and give extra information on a surface previously not constrained by aeromagnetic and satellite data. This implies a better determination of the coefficients governing the magnetic field altitude variations. Although in the real case we are dealing with imperfect and noisy repeat station data, we conclude that including the repeat station measurements greatly reduces the ambiguity about the vector components at every altitude and is important for upward/downward continuation purposes.

3.3 Anomaly vector maps for Germany

In order to study the consistency between all data and evaluate the data uncertainties and biases at repeat stations, we derived two models for comparison: model 1 based only on the aeromagnetic and satellite data and model 2 additionally including the repeat station anomaly data. In agreement with the prior study on synthetic data the statistical difference between model 1 and model 2 is low. The residual mean square for each data set is computed and the respective statistics are summarized in Table 7. By including the repeat station data in the modelling, the fit to these data can be significantly improved. This seems to make almost no difference for the anomaly intensity values, but we observe a significant change when comparing both vector models.

The misfit to aeromagnetic data is slightly higher than the estimated uncertainties of ±10 nT, likely because the model resolution (37 km) does not fully agree with the maximum resolution of 25–30 km for a 5 × 5 km grid. The fit to satellite data is very good and demonstrates the quality of CHAMP measurements and data processing. Since scalar data are less sensitive to external field variations, the fit is better for scalar than for vector data. Other results, not shown here, reflect that vector components *X* and *Y* are in general noisier than the *Z* component for all vector data sets. Repeat stations have the highest residual mean square, reflecting both a lack of resolution in the modelling and a compatibility limit between repeat stations and aeromagnetic data. However, regarding the absence of control on the aeromagnetic data and their corresponding problems discussed above (Section 2.4), it is impossible to conclude if the relative mismatch is due to repeat station measurements error, to bad levelling and positioning of the airborne data or simply to insufficient resolution of the model. The improvement of fit to the repeat station data in model 2 slightly affects the fit to the other data sets, particularly to the satellite data, indicating a good, but not perfect compatibility of the different types of data within our modelling method.

Table 7. Fit of the two models to aeromagnetic, repeat stations and CHAMP data sets.

	Aero. data	Repeat stations	Vector CHAMP	Scalar CHAMP
rms model 1 [nT]	13.2	35.1	0.4	0.3
correlation model 1	0.97	0.78	0.99	0.99
rms model 2 [nT]	13.6	22.4	0.6	0.4
Correlation model 2	0.97	0.93	0.98	0.99

Figs 4–6 show the prediction of the magnetic anomaly field component at the mean Earth radius from model 2. Considering our synthetic analysis and a distortion that could reach 2 per cent of the model, we estimate the maximum Gibbs error near edges at this surface to be 7 nT for *X* and *Y*, and 8 nT for *Z*; this is less than the aeromagnetic or repeat station data residual mean square (Table 7). In order to check the reliability of the prediction, we further compare our model with data from five French repeat stations, which have not been used in the modelling. These five stations lie precisely near the edges of our models. The correlation between model 2 and these data is 0.79 and the residual mean square is 26 nT, with only 12 nT for just the *Z* component. These results are in good agreement with the model statistics (Table 8). Moreover, magnetic anomaly charts for France are described in Thébault *et al.* (2006a) and we notice a good continuity in the entire overlapping area between the results obtained there and the maps presented here.

3.4 Repeat station biases

We now focus on the magnetic field prediction at the repeat station locations in order to evaluate the crustal biases. In Table 8 the rms misfits per component between the repeat station crustal field data and both our models are summarized, together with the misfit to the lithospheric description of CM4 (spherical harmonic degrees 15–60) for comparison. The improvement of the regional models over CM4 due to increased resolution is significant, even when the repeat station data were not used in the modelling. Even for model 1, where the mean square residuals remain as high as 45.1 nT for *Z*, the correlation is better than 0.80 for all three components of the field. The comparisons in Figs 7–9 show that the R-SCHA predictions under or overestimate the field but that the spatial variation of the models are generally consistent with the measured values. A global model like CM4, to the contrary, correlates poorly with repeat stations, especially for the *Y* component. Occasionally, the crustal anomaly values of CM4 even have opposite sign and the differences with the repeat station data reach up to 173 nT (station col). The offsets between the CM4 predictions and the observatory mean data are also high, although these data were used in the construction of that model. It is clear that the spatial resolution of CM4 at the ground (about 620 km) is insufficient to take regional and local variations into account and the statistics reflect this low resolution. To some extend, we have a similar limitation at the regional scale which is the reason for the rms values even of model 2 being much higher than the estimated data uncertainties (see Fig. 3 and Table 5), although the model is more consistent with the values recorded at the repeat stations.

4 DISCUSSION AND CONCLUSIONS

The crustal anomaly values for the individual repeat stations were obtained as averaged values from observations in different years

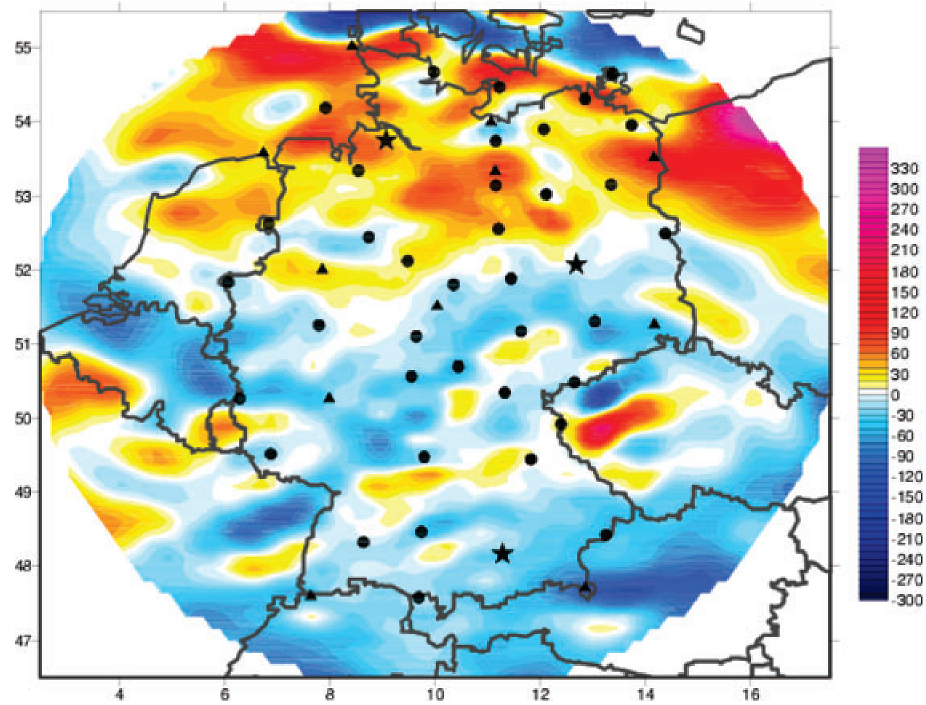

Figure 4. *X* component of the crustal field at the mean Earth radius in nT. Repeat station positions are marked by dots, triangles where a local variometer was used since 1999, and stars mark the positions of the three German observatories.

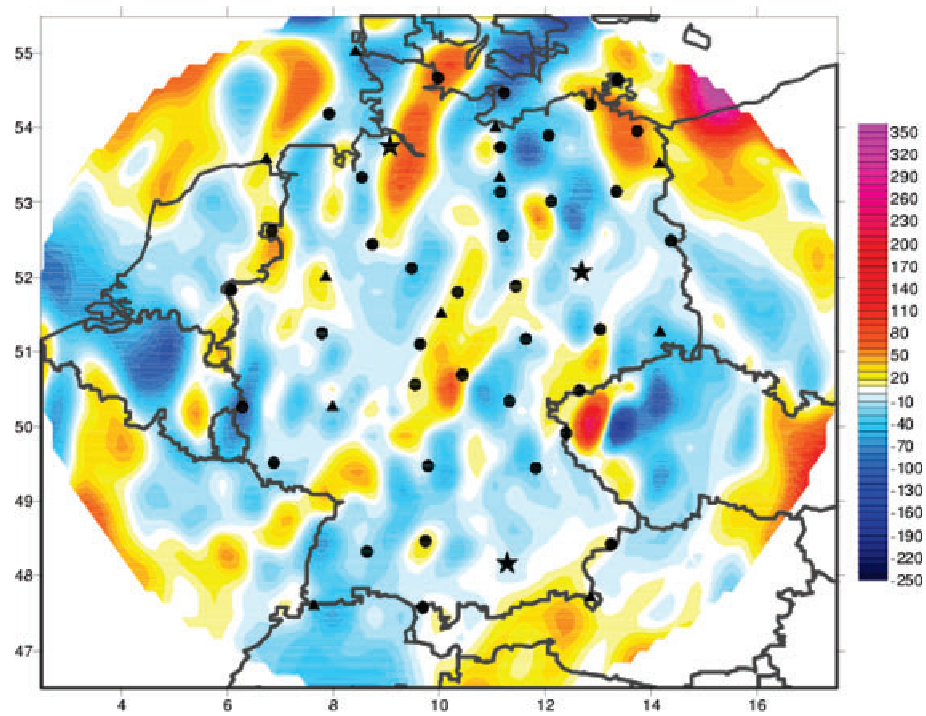

Figure 5. *Y* component of the anomaly field at the mean Earth's radius in nT, symbols as in Fig. 4.

with the CM4 core field and secular variation model subtracted and a correction for external field signal in annual mean values. Apart from the true crustal station biases which should be nearly constant with time the data might include data errors (including external field influences which were not properly eliminated by the initial reduction or annual means correction) and main field residuals if the CM4 secular variation description should be insufficient. The slight long-term trends in the observatory data after subtraction of CM4 suggest that this description is indeed not perfect, but the effect in all the observatories' components is less than 0.14 nT yr^{-1}. We do not expect significantly stronger deviations at individual repeat stations. The high correlation and good general agreement between

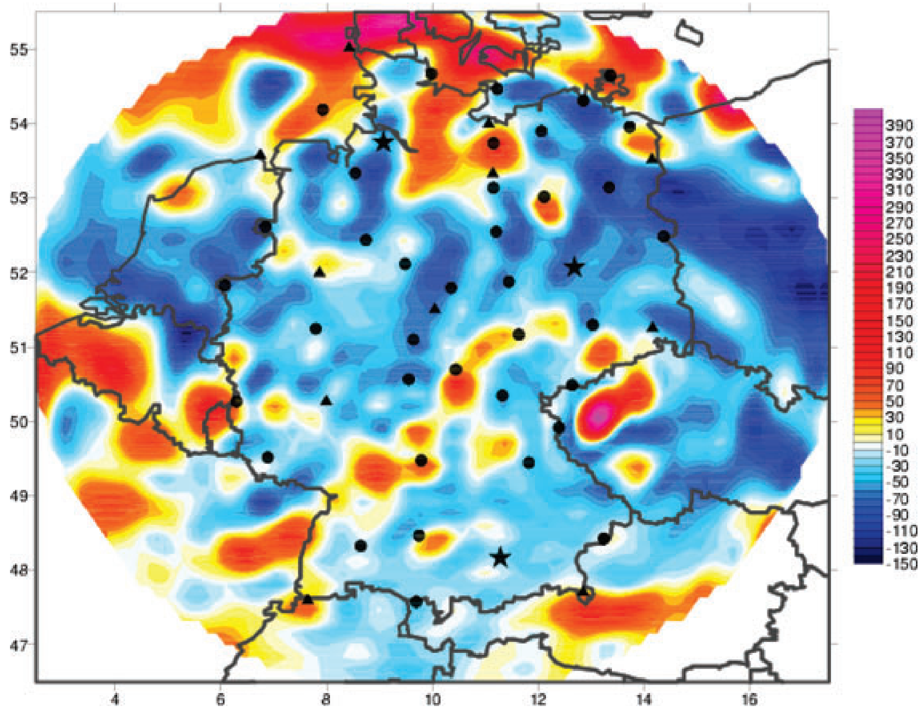

Figure 6. *Z* component of the anomaly field at the mean Earth's radius in nT, symbols as in Fig. 4.

Table 8. Residual mean squares (rms)and correlation factors R for each components between R-SCHA model with (model 2) and without (model 1) repeat station data and actual repeat stations mean values. For comparison, the same statistics are presented between the CM4 model and the data.

	X_{CM4}	Y_{CM4}	Z_{CM4}	X_1	Y_1	Z_1	X_2	Y_2	Z_2
rms (nT)	50.9	40.0	69.2	33.8	22.8	45.1	23.4	17.0	26.0
R	0.51	0.03	0.36	0.84	0.82	0.88	0.91	0.91	0.97

the repeat station crustal anomaly data and our regional models indicates that crustal biases are represented well by these data. The standard deviations from averaging the results of individual years can be taken as reasonable uncertainty estimates. These are much smaller than the misfit of our best model, model 2, to the data. We suppose that this discrepancy is due to the limited resolution of the aeromagnetic data and the model and conclude that the crustal anomaly values presented in Table 6 can be regarded as the repeat station crustal biases.

The uncertainty estimates, however, vary a lot between individual stations. It is noteworthy that quite often only one of the three components displays a large scatter and general conclusions about the quality of individual stations are hardly possible. The stations where the local variometer was used during the last years in general are among those with the lowest scatter, as expected. Larger values, like in the *Y* component at Deutschbaselitz (deu) or in *X* and *Y* at Goesslow (goe) and Kobletz (kob) are at closer inspection explained by very large scatter or outliers in the earlier data. Uncertainties due to less precise instruments used in the earlier surveys might add to errors from insufficient external and induced field correction without local variometer. At Goettingen (gtt) and Telgte (tel), the stations had been moved to slightly different locations both in 2000 and Telgte again in 2002. The exact differences in magnetic field values could not be determined and seemed insignificant for this work in comparison to the scatter seen in other stations. The standard deviation for the values obtained with the local variometer are much lower if only the new stations are considered. For Warnkenhagen (war) we discovered a strong cultural disturbance near the station and actually had to give up measurements in that area in 2004. We kept the data in this study because the problem seems not to affect the data in a systematic way, but the uncertainties of these data clearly are high.

The resolution of the aeromagnetic data compilation that was available for R-SCHA modelling was limited to no better than 25 km. However, the differences between model and repeat station data may be explained not only by the low resolution of the aeromagnetic values but also by the modelling technique. A special effort remains to be done in order to enable the R-SCHA modelling to represent the magnetic field up to 5 or 10 km resolution. Such a high resolution is difficult to reach due to convergence properties of eq. (3). For this reason, it remains also difficult to estimate the data quality and compatibility from the comparison to the model. For instance, when considering only the station with local variometer, we detect a slightly better fit between the data and the model but, first, the number of data is too low to establish proper statistics on these data only and secondly the model resolution is probably insufficient. In the future, the bias might be reduced by using more detailed aeromagnetic surveys but still repeat stations may lie on localized anomalies not even properly detectable at aeromagnetic altitudes. We suppose that the influence of ground vector data to improve the accuracy of a model becomes amplified in devising very high resolution models. Interestingly, the maximum deviations are observed in the *Z* component (Fig. 9) for the repeat stations Altenkirchen (alt), Buggow (bug), Grumbach (gru) or Hoppenrade (hop), for instance, which lie over magnetic anomalies of small extension. The exact location of the maximum anomaly amplitude is probably not clearly detected by aeromagnetic compilations, but is recorded by the repeat station measurements. In setting up repeat stations in general one should try to avoid known local magnetic anomalies, but such anomalies might not be known and a check for homogeneity of the field at a station usually covers a few meters to a few tens of meters at the most. Repeat station data thus can really contain very local crustal field

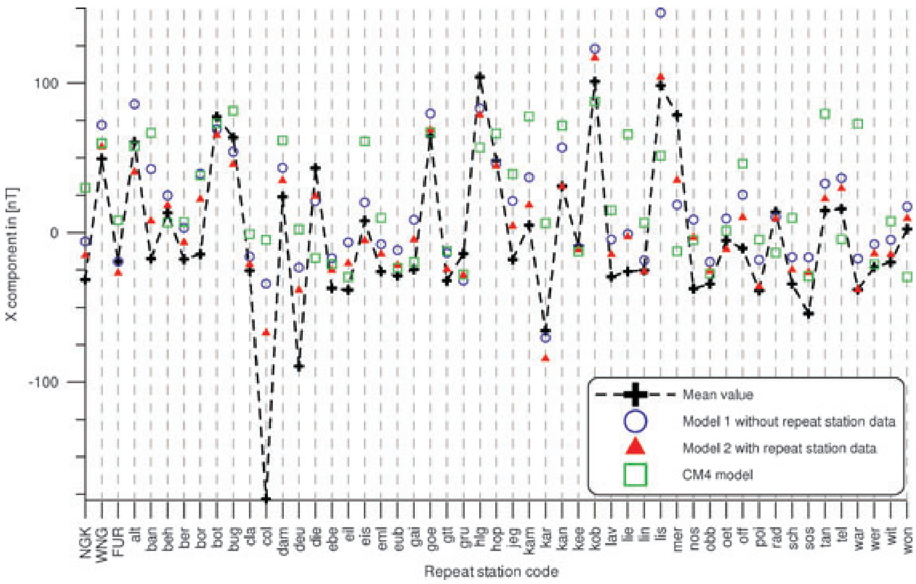

Figure 7. Comparison between CM4 prediction, R-SCHA predictions and the repeat stations mean crustal values for the *X* component. The dashed line connects points for easier orientation only, the stations are ordered alphabetically, not geographically.

contributions. Aeromagnetic measurements, on the other hand, are sensitive to larger scales and the regional background is important when comparing aeromagnetic and repeat station data. Some stations, like Helgoland (hlg), Karlstein (kar) or List (lis) also lie over strong magnetic anomalies but the deviation between both data sets is less since the anomalies have a much larger extension (Fig. 9). The same applies to negative anomalies with homogeneous magnetic signature over large extensions like over Clausthal (cla), Collm (col), Keeken (kee) or Göttingen (gtt), for which we notice a good agreement. This is also true in general for the components *X* and *Y* shown in Figs 7 and 8.

The comparison of two regional models with and without the repeat station data showed the importance of a good coverage by ground vector data when devising regional vector anomaly field models with upward/downward continuation ability. In principle, one single ground vector survey would suffice. When repeat station data are available the redundancy of data provides a more robust estimate of the lithospheric field contribution to the data (i.e. the crustal bias at that location). This is desirable in view of the difficulties in properly correcting for external field contributions and their induced counterparts in discrete ground measurements. The best-fitting model can provide useful vector information for quantitative studies about the sources of the magnetic anomalies and their variation with altitude, where previously only aeromagnetic intensity data at one altitude were available. To some extent, it may be possible to restore the correct baseline in aeromagnetic compilations. Model 2 provides a good description of the anomalies over the region of Germany. As with all regional methods the borders of the studied region should be regarded with caution, in particular as we did not include repeat station data from neighbouring countries.

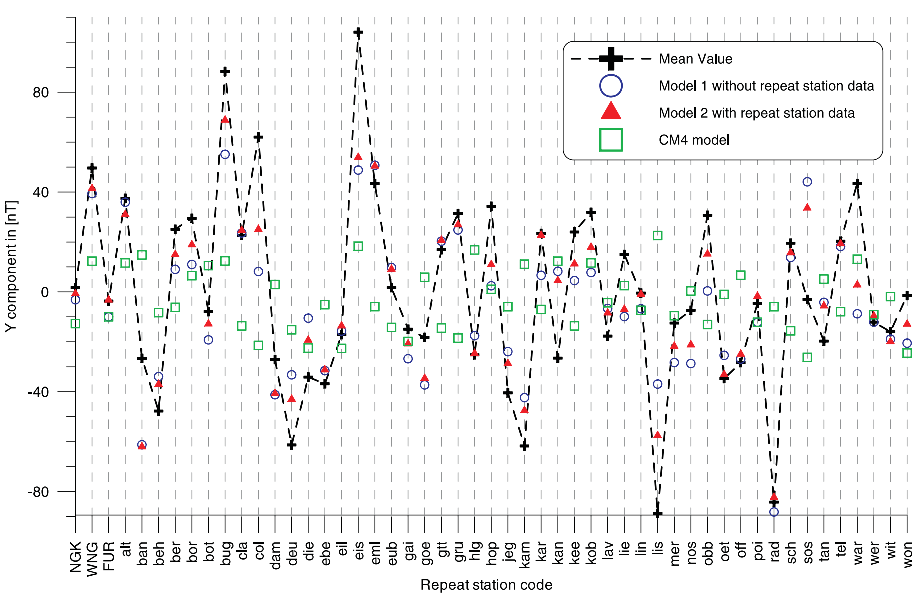

Figure 8. Comparison between CM4 prediction, R-SCHA prediction and the repeat stations mean values for the *Y* component as in Fig. 7.

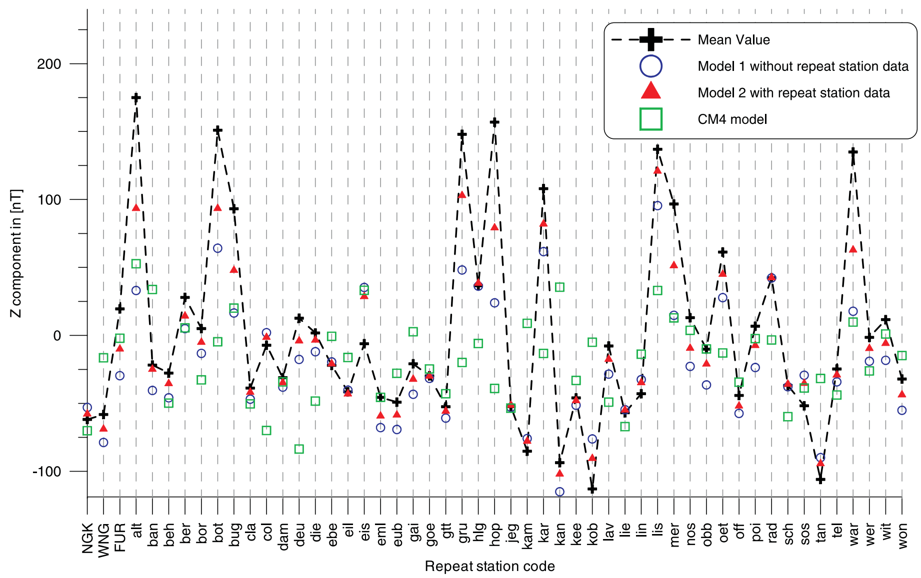

Figure 9. Comparison between CM4 prediction, R-SCHA prediction and the repeat stations mean values for the *Z* component as in Fig. 7.

The earlier repeat station data from different countries are so different with respect to both spatial and temporal distribution that we didn't consider an inclusion of the few data lying within our model area worth the effort. The upcoming data produced by the European countries within the MagNetE initiative will provide a basis for vectorial magnetic anomaly models on the continental scale.

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