GeoForschungsZentrum Potsdam

Stiftung des öffentlichen Rechts

Scientific Technical Report

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Magnetic repeat station survey of Germany 1999/2000

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1. Introduction

A new magnetic repeat station survey was carried out in Germany in 1999 and 2000. It is the third regional magnetic survey in reunited Germany after the first common survey of 1992.5 (Beblo et al. 1995, Schulz et al., 1997b) and one of 1996.5. It also is the second real repeat station survey on a fixed network, with a projected reoccupation interval of 2 years. Although in former surveys many stations could be reoccupied the networks of stations changed significantly between successive surveys. The only true repeat station surveys (cf. Newitt et al., 1996) in Germany were annual measurements in the former GDR between 1985 and 1988. The main German surveys prior to the 1992 survey are for 1982.5 (Schulz et al. 1997a) and 1965.0 (Voppel and Wienert, 1974) for former Western Germany, 1990.5 and 1957.5 (Bolz et al., 1969) for former GDR and one for 1935.0 (Bock et al. 1948 and 1956) for the whole area of Germany at that time. Information about additional magnetic surveys of only parts of Germany, particularly older ones, is given by Weingärtner (1991).

There are slight but important differences between regional ground vector surveys and repeat station surveys (Newitt et al., 1996): The aims of ground vector surveys are to obtain detailed maps of the absolute values of the geomagnetic field, e.g., for navigational purposes and sometimes for crustal anomaly studies. Good spatial resolution is desired, so they are carried out on dense networks. They do not have to be repeated very frequently and reoccupation of the same sites is not important. In contrast, the purpose of repeat station surveys is to study secular variation. They have to be carried out every few years at precisely located points because of the variability of secular variation. The network of repeat stations does not have to be as dense as that of a ground vector survey. However, the desired accuracy of the data is higher, so as to obtain smaller relative errors given the small amplitude of secular variation.

Aside from serving scientific secular variation studies, the secular variation models obtained from repeat station data can be used to update the spatially more detailed magnetic maps from earlier ground vector surveys. That was the motivation for the decision to start frequent repeat station surveys in 1998, mainly on the network of the 1996 survey.

A three-component variometer was used in addition to the absolute measurements to allow for the higher accuracy demanded in repeat station surveys. Newitt et al. (1996) recommend the use of an in-situ variometer, and Korte (1999) demonstrated that external magnetic variations might be a significant part of the errors of regional survey data. Even if the distance to the nearest observatory is not extremely great for the German repeat stations, there are significant changes in the electrical conductivity of the subsurface, and thus in the induced part of the magnetic field.

In this report we describe the new repeat station network, the measurements and some tests regarding the use of the variometer recordings for data processing, and we present the results of this latest German magnetic survey.

2. Regional magnetic survey data processing

The first results of a regional magnetic survey are magnetic field values measured at the stations at different days within one or a few years. Such values are not directly comparable and cannot be used to produce any charts because of the variations of the geomagnetic field, both short-period external field variations and main field secular variation. The desired results are values of the internal magnetic field alone, and for all stations for a common epoch, usually annual mean values which can be compared to those produced by geomagnetic observatories.

2.1. Traditional Method

In the traditional method observatory recordings are used for the reduction of the measured data to annual mean values:

$$C(x_i,t_{mean}) = C(x_i,t_i) - C(O,t_i) + C(O, t_{mean}) \quad (1)$$

$C(x_i,t_i)$ is the value of geomagnetic component C at location x_i and time t_i, x being the repeat station, O the observatory, t_i the time of the observations at repeat station x and t_{mean} the annual mean centred at the desired epoch (e.g. Newitt et al., 1996). The difference $C(x_i,t_i) - C(O,t_i)$ will generally be an average of at least two absolute measurements at the station, in other words, averaged over several times t_i. This difference is the critical part to be determined correctly, $C(O, t_{mean})$ only is the constant observatory annual mean value of the desired year.

Equation (1) is based on the assumption that all geomagnetic variations, both external and secular variation, are the same at the observatory and the repeat station. As this is not the case, errors arise. These reduction errors depend on the distance between the station and the observatory, the electrical conductivity beneath the two locations and the secular variation gradient. More detailed information on such errors is given by Newitt et al. (1996) and, with numerical examples for the mid-European region, by Korte (1999).

In general the secular variation gradient is small enough in Germany to make those errors negligible when reducing over time spans of less than one or two years. However, the differences in external field, and particularly differences in the resulting induced part of the magnetic field due to differences in ground conductivity are a real problem, as the examples in section 3.2 will demonstrate.

2.2. Method using an in-situ variometer

A variometer set up close to the survey points can minimise errors due to differences of external variations between repeat stations and observatories. The variations of e.g. the components H, D and Z are measured as at an observatory for one to several days. The results of the absolute measurement are used to determine the base line and thus absolute values of the variometer recordings. To obtain an annual mean value it is still necessary to use the recordings of an observatory. However, it now is possible to use quiet night time values in equation (1) instead of the instantaneous values $C(x_i,t_i)$: the difference $C(x_i,t_i) - C(O,t_i)$ now is calculated as an average over many quiet night time values, e.g. hourly means of such values. The assumption now is that the night time displacement at the repeat station is the same as at the observatory. Quiet night time values come closer to the desired undisturbed internal field so the errors due to external influences should be significantly smaller than when using only instantaneous values (cf. Newitt et al., 1996).

3. The 1999/2000 repeat station survey

3.1. Measurements

The new German repeat station network was introduced in the 1996 survey. It consists of 45 stations (Fig. 1). Most of the sites have already been used in the earlier magnetic ground vector surveys of Germany and are well-defined by non-magnetic markers. The mean distance between the stations is approximately 150 kilometres. The measured field components are declination, inclination and total intensity. The absolute instruments used are a DI-fluxgate theodolite (Zeiss with Bartington magnetometer) for the measurements of declination and inclination and a proton magnetometer GSM 19 for total intensity. Two sets of components are measured in the order F, D, I, D, I, F within a time span of 1 to 2 hours. During the angular measurements F was recorded with the proton magnetometer some metres from the station for control and comparison with the variometer recordings with a sample rate of 5 seconds. At several stations a gyro-theodolite GP1 2A was used to determine the azimuths.

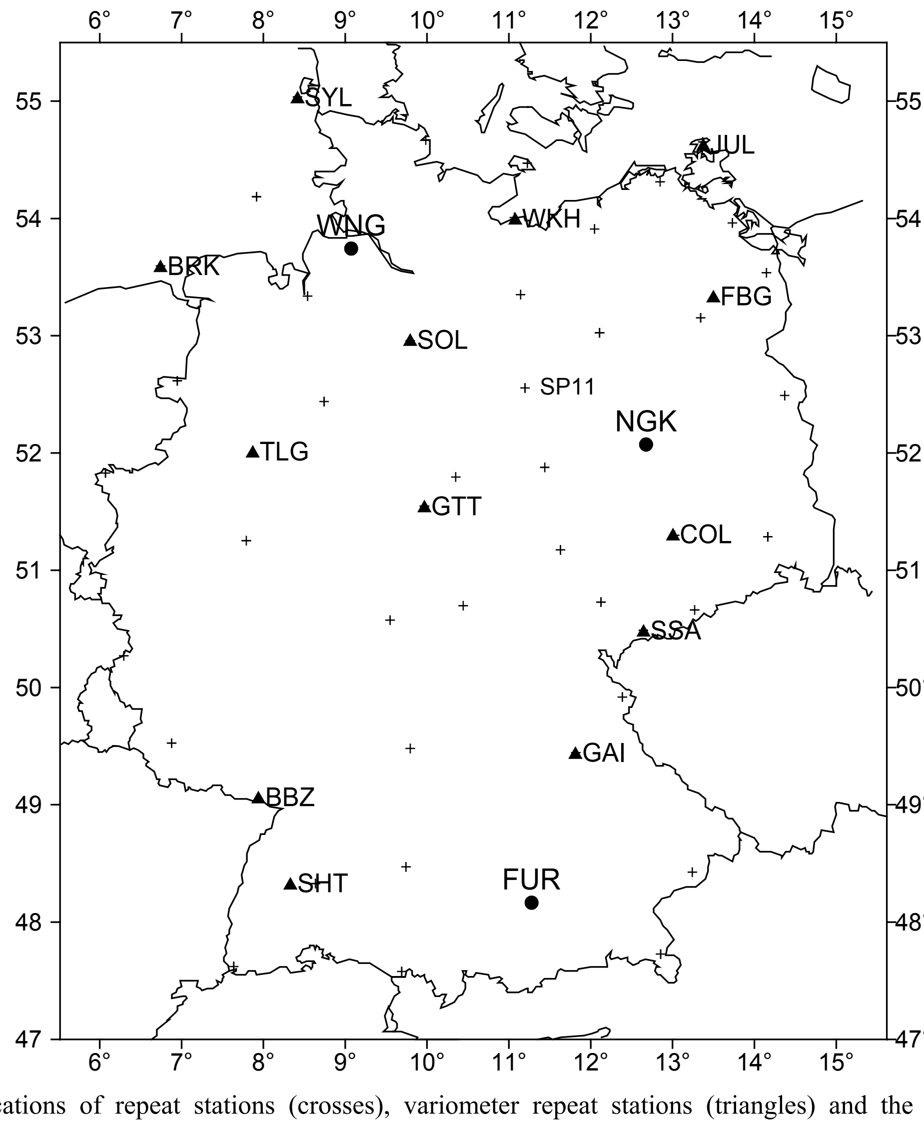

Fig. 1: Locations of repeat stations (crosses), variometer repeat stations (triangles) and the three German geomagnetic observatories Wingst (WNG), Niemegk (NGK) and Fürstenfeldbruck (FUR).

As the effort of putting up a variometer at every single one of the 45 stations for several days would be prohibitive, we had to compromise and use central variometer stations instead. A variometer station is set up at central repeat stations for several days while absolute measurements are done at the neighbouring stations. We thus have a system of first and second order points: a sparse network of stations where external variations are determined excellently, and additionally a network of stations with good spatial resolution, where the external variations still can be accounted for to a high level. The distance between variometer and repeat stations does not exceed 150 km. The variometer was maintained at one location long enough for the recordings to include quiet night time values with K-index at the Niemegk observatory no greater than 1.

The instrument used is a three component fluxgate magnetometer LEMI 008 with sampling rate 1s, oriented to measure H, D perpendicular to H in nT and Z. The variometer has a remarkably good baseline stability, even comparable to observatory instruments, as confirmed by several test recordings at the Niemegk observatory, where the instrument was set up in the same way as in the actual repeat survey. Temperature effects of the electronics proved negligible in those tests, and temperature effects of the sensor can be accounted for by determined coefficients. In any case, the variation of sensor temperature could be kept smaller than 2° by burying the sensor about 50 cm deep in the ground.

Additionally, a proton magnetometer GSM 19 to record F with a sample rate of 10 to 20 seconds was used.

All repeat and variometer stations were rechecked for magnetic homogeneity prior to the measurements. Several comparison measurements at the Niemegk, Wingst and Fürstenfeldbruck observatory were made with all instruments prior to, between and after the measurements at the repeat stations.

3.2. Processing and comparison to traditional method

All recordings are checked visually for artificial disturbances and compared to observatory recordings. Fig. 2 shows how much difference there might be between the variations at different stations: the comparison shows data from the variometer station SYL and the observatories WNG and NGK. Fig. 2a shows the variations of H, D and Z recorded at the 3 locations. On first sight they do not seem to differ too much, but a closer look at the differences between SYL and NGK (Fig. 2b) and SYL and WNG (Fig. 2c) proves otherwise. That there are large differences in the variations between SYL and NGK, about 400 km apart, is not unexpected. However, the distance between SYL and WNG only is about 150 km. With more than 10 nT the differences in the external / induced variations reach surprisingly large values here. The differences in quiet night time values, however, do not vary much even between Sylt and NGK, showing clearly the advantage of the variometer.

It is well-known that there are significant induction anomalies in northern Germany (e.g. ERCEUGT Group, 1992), yet we sometimes underestimated the effect. Fig. 3 shows a comparison of repeat station SP11, Niemegk observatory (NGK, about 150 km away) and the variometer station FBG. SP11 was thought to be close enough to NGK, so no variometer was set up there. The curves that are shown are the proton magnetometer F recordings from station SP11 during the angular measurements and the F-recordings of FBG and NGK for the same time span. For comparison all curves are normalized to zero as first value. The variation recorded at SP11 differs by up to 10 nT from the variation at NGK. Moreover, the effect is reversed between the stations SP11 and FBG, giving differences of up to 20 nT for those stations less than 200 km apart. Conditions were magnetically disturbed (K=4). Nevertheless, this example shows what high influences of external variations and resulting low accuracy regarding the internal field we may have in the results for stations without a variometer.

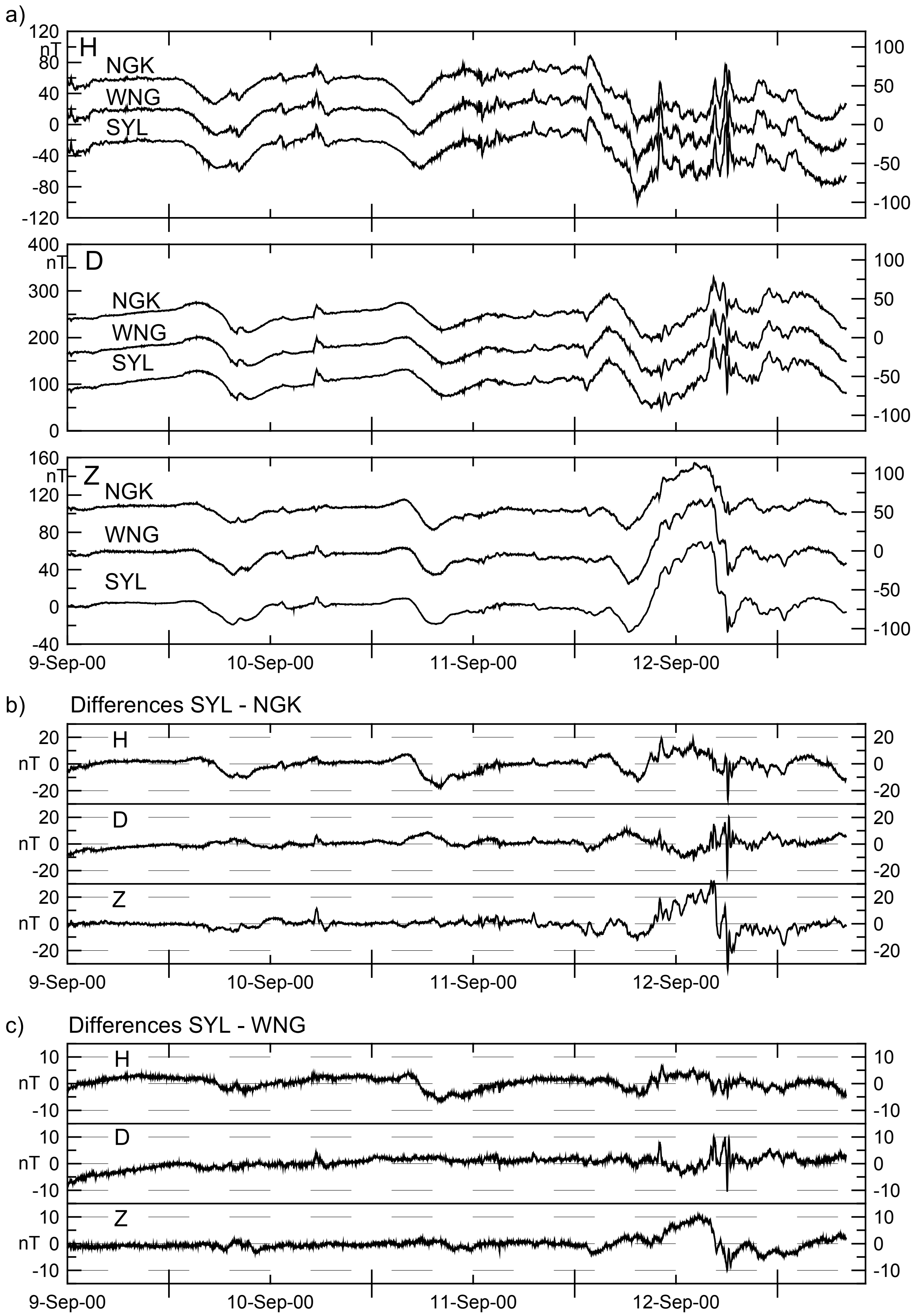

Fig. 2: Recordings of the variometer station SYL and the observatories WNG and NGK and differences respectively. All values are relative for comparison. Note the different scales in b) and c).

The situation is not quite so bad in other regions where gradients of conductivity are less strong. Table 1 shows examples of 3 repeat stations that all have been measured twice: once directly as variometer station and a second time when the variometer was recording at one of the neighbouring variometer stations. Additionally the values that would result using only the Niemegk observatory for reduction are given (momentary values). For the location of the three stations and the additional variometer stations see Fig. 1. The differences in the quiet night time results are less than 3 nT in H and Z and, except for GAI, not more than 0.3' in D. The momentary values without any variometer vary much more, e.g., at GAI in H by more than 10 nT. As expected, even the average of those values can lead to results different by several nT from the results obtained by taking quiet night time values, as for example in the Z component of GAI.

Table 1: Results for 3 Stations if Measured as Variometer Stations or with the Variometer about 100 km Away

Day/Variometer	ΔH (nT)		ΔD (′)		ΔZ (nT)	
K-index	Quiet Night	Momentary	Quiet Night	Momentary	Quiet Night	Momentary
Repeat Station GAI						
211/SSA K=4	1374.0	1369.1 1381.8	-16.0	-15.8 -15.0	-1369.5	-1371.0 -1376.5
231/GAI K=3	1373.3	1372.0 1368.6	-16.7	-17.1 -17.5	-1366.7	-1375.1 -1374.1
Repeat Station COL						
214/SSA K=2/3	245.6	249.6 245.1	18.0	17.9 17.8	-300.8	-304.7 -302.8
172/COL K=2	244.3	244.6 243.3	17.9	17.8 17.8	-302.9	-304.2 -303.8
Repeat Station SHT						
223/BBZ K=2	2008.2	2013.5 2010.2	-71.1	-71.7 -71.4	-2173.1	-2179.9 -2178.1
239/SHT K=2/3	2005.9	2006.3 2007.6	-71.4	-71.3 -71.9	-2172.9	-2174.0 -2174.6

The values are the differences to the Niemegk observatory ($C(x_i,t_i) – C(O,t_i)$ from equation 1). Column 1 gives the day of the measurement and the variometer station used for reduction. The "quiet night" values are the values actually obtained using the variometer, the "momentary" values are the values obtained using no variometer station but only the Niemegk observatory recordings for reduction.

Summarizing the results so far we can state that central variometer stations are an improvement to using only observatory values for reduction of repeat station measurements. However, we really should differentiate between the data from very high accuracy variometer repeat stations and the rest of the repeat stations.

Baseline values

During the processing there are several other steps where the advantages of the variometer are evident. The following example not only shows the baseline stability of the variometer, but also that the accuracy of the measurements is less of a problem than the external / induced variations.

Table 2 gives the baseline values determined from absolute measurements at the variometer station SSA on Juli 27 and August 3, 1999. The values differ by less than 1 nT in Z, less than 2 nT in H and less than 0.2' in D, confirming an excellent baseline stability of the used variometer. The fact that the values do not change significantly between the separate absolute measurements of the 2 days shows that the accuracy of the measurements themselves is very good. For comparison, Table 3 shows the baseline values resulting for the NGK variometer from the same measurements. We know that the real baseline of that observatory instrument is stable, so variations are due to the difference in the external / induced variations at the location of the variometer (NGK) and of the absolute measurements (SSA). The values differ by more than 1 nT in Z up to 5 nT in H. In our processing with central variometer stations this can be a hint as to whether the variations at the variometer station and a remote repeat station are similar as assumed. If the determined baseline values differ significantly, than it is most likely that the variations are not as similar as hoped for.

Table 2: Baseline Values of Variometer SSA Determined from Measurements at that Repeat Station

Date	Time	Baseline H	Baseline D	Baseline Z
27.07.1999	10:11	19591.45	1° 22.51'	44267.54
	11:16	19590.91	1° 22.64'	44267.77
08.03.1999	7:59	19592.79	1° 22.53'	44267.56
	9:40	19592.69	1° 22.49'	44267.60

Table 3: Baseline Values of Variometer NGK Determined form Measurements at the Repeat Station SSA

Date	Time	Baseline H	Baseline D	Baseline Z
27.07.1999	10:11	19522.11	0° 38.66'	44135.85
	11:16	19520.68	0° 38.79'	44136.48
08.03.1999	7:59	19517.44	0° 38.93'	44135.37
	9:40	19516.94	0° 38.58'	44135.58

Quiet night time differences

The next example, Table 4,confirms numerically what was already shown in the curves in Fig. 2: the differences of the quiet night time values really do not vary much and thus can be expected to represent well the difference between the undisturbed internal field at the two sites.

Table 4: Differences Between Variation Recordings at TLG and Niemegk Observatory Values in Quiet Night Times

Date	UT	Hourly mean values		
		ΔH (nT)	ΔD (′)	ΔZ (nT)
25.07.2000	22	-18786.2	-77.7	-45075.9
25.07.2000	23	-18786.2	-77.8	-45076.3
28.07.2000	21	-18786.4	-77.7	-45075.5
28.07.2000	22	-18787.0	-77.7	-45075.4
28.07.2000	23	-18786.4	-77.6	-45075.2

Several examples

Finally we give some more comparisons of the results obtained by using quiet night time values, that is variometer stations, and only recordings of the Niemegk observatory, that is momentary values. The results shown in Table 5 are again differences to Niemegk values (the difference $C(x_i,t_i) - C(O,t_i)$ from equation 1). The momentary values vary by up to 10 nT, and even the average sometimes is more than 10 nT different from the result of quiet night time values, assumed to be the proper difference of the internal magnetic field between the station and NGK. Note that the results of repeat stations far from variometer stations are not necessarily much worse, even if measured in magnetically disturbed conditions: The station Tangersdorf is very close to the variometer station FBG, but more than 100 km distant from Niemegk observatory. However, the quiet night time values obtained using FBG and the

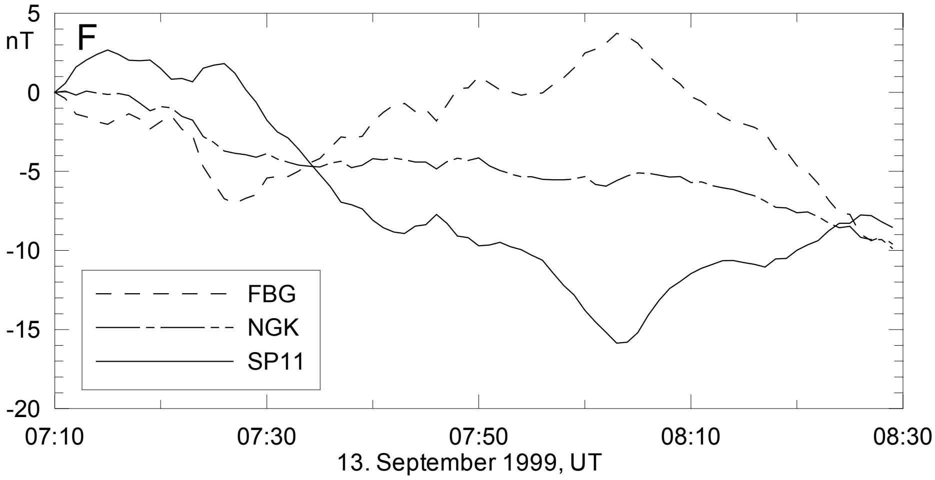

Fig. 3: F-recordings at repeat station SP11, variometer station FBG and Niemegk observatory (NGK). For location of the stations see Fig. 1.

momentary values using only NGK do not differ very much. Remembering the differences of the recordings at FBG and NGK (Fig. 3) this is astonishing. However, we want to take this as a warning again: much as some results of remote repeat stations suffer from external influences less than expected, others not even too far away might contain such influences to an astonishing high degree. The fact that measurements have been done under magnetically quiet or disturbed conditions is also not sufficient to tell how good the accuracy of the results is. If we want to be sure to get results as free from external influences as possible the only method is to occupy the station as a variometer station and record long enough to include quiet night times.

Table 5: Example Results (Differences to NGK)

	ΔH (nT)		ΔD (′)		ΔZ (nT)	
day/variometer	quiet night	momentary	quiet night	momentary	quiet night	momentary
repeat station Warnkenhagen (WKH)						
285/WKH K=3/4	-935.4	-951.6 -954.1	-31.1	-29.7 -29.4	998.9	983.2 984.5
repeat station Karniner Holz						
290/JUL K=3	-1051.5	-1045.6 -1055.0	-1.1	-1.7 -1.4	1013.1	1015.3 1019.0
repeat station Hoppenrade						
256/FBG K=3	-391.6	-388.7 -383.1	-6.0	-5.9 -5.8	635.0	642.8 640.5
repeat station Tangersdorf						
252/FBG K=4	-503.1	-505.9 -503.5	8.6	8.4 8.3	509.7	511.6 510.8

"Quiet night" are the values obtained using a variometer station, "momentary" values are obtained without additional variometer station.

4. Results

Tables 6 and 7 list geographic coordinates and final results of all repeat stations reduced to 1999.5, including the annual means of the three German observatories. Generally we used the nearest variometer station or observatory for the data reduction. In cases where there were indications that the variations at the nearest station might still differ significantly from those at the repeat station, we used the comparison with the F-values recorded during the absolute measurements and the stability of the two baseline values to decide whether to take as final results the results using the variometer station or an observatory. In some cases, when distances to variometer station and observatory were equal and the F-recordings of the variations at the repeat station differed from those at the observatory and the variometer station by the same order of magnitude, the final result was taken as the average of the results of both ways of processing. Which variometer station was used for the reduction is included in Table 6.

Additionally, the results are given separately for the points measured in 1999 and 2000 respectively (Table 8). These values are given as differences to the Niemegk observatory to allow easy reduction to the corresponding years or to either 1999.5 or 2000.5 for all of the points. Fig. 4 shows maps interpolated from the results for horizontal intensity, declination and vertical intensity. Table 9 gives an overview over the maximum and average residuals for these models. A comparison with an aeromagnetic map of total intensity crustal anomalies (Wonik et al., 1992) confirms that high residuals generally appear for stations situated on local magnetic anomalies, where the interpolation smoothes (and distorts) such small scale structure. Only the declination value at station 3024 (Mittelstendorf) looks somewhat spurious, but that station has not been measured in the last two surveys. We bracketed this result in the tables and did not consider it for the interpolated chart. The decision whether to include or reject this value requires further measurements at that station.

Fig. 5 gives second order polynomial normal field models for all magnetic components, calculated as:

$$C(\lambda,\varphi) = a_1 + a_2 (\lambda - \lambda_0) + a_3 (\varphi - \varphi_0) + a_4 (\lambda - \lambda_0)^2 + a_5 (\lambda - \lambda_0)(\varphi - \varphi_0) + a_6 (\varphi - \varphi_0)^2 \qquad (2)$$

for the geomagnetic component C at the station with longitude λ and latitude φ. The coefficients a are determined by a regression (a_1 [°], a_2, a_3 [1/°], a_4, a_5, a_6 [$(1/°)^2$] for D and I; a_1 [nT], a_2, a_3 [1/nT], a_4, a_5, a_6 [$(1/nT)^2$] for the other components). The origin was chosen as λ_0 = 10° and φ_0 = 50°. The coefficients determined are listed in Table 10. Maximum and average residuals between the data and those models are also included in Table 9.

Table 6: Repeat Station Information

Longitude	Latitude	Stat. Nr.	Station	Height [m]	Variometer
8.417	55.036	916	List;Moevenduene	11	SYL
9.984	54.669	1325	Eiskeller	56	WNG
13.367	54.652	SP1	Altenkirchen	20	JUL
11.225	54.471	1533	Bannesdorf	10	WKH
12.847	54.312	SP2	Karniner_Holz	10	WKH
7.916	54.185	1813	Helgoland;Duene	2	SYL
11.068	54.008	SP3	Warnkenhagen	13	WKH
13.730	53.962	SP5	Buggow	24	FBG
12.047	53.910	SP4	Kambs	30	FBG
6.744	53.596	2306	Borkum;Sueddeich	2	BRK
14.147	53.537	SP7	Koblentz	10	FBG
11.142	53.350	SP8	Goesslow	13	FBG
8.541	53.337	2617	Offenwarden	0	SOL
13.342	53.152	SP9	Tangersdorf	62	FBG
12.107	53.025	SP10	Hoppenrade	65	FBG
9.794	52.958	3024	Mittelstendorf	80	SOL
6.949	52.615	3307	Kleinringe;Steenvenn	16	BRK
6.838	52.623	3307n	Emlichheim	15	BRK
11.197	52.555	SP11	Jeggau	70	NGK
14.368	52.490	SP12	Lietzen_Vorwerk	50	NGK
8.743	52.438	3518	Lavelsloh	48	TLG
7.870	52.013	4012	Telgte	60	TLG
11.438	51.877	SP14	Schneidlingen	140	NGK
6.071	51.829	4102	Keeken;Wey	12	TLG
10.351	51.795	4228	Clausthal;2_Muehlenberg	601	GTT
10.045	51.531	4425	Goettingen;Warteberg	289	GTT
13.025	51.298	124	Collm	200	COL
14.163	51.285	SP16	Deutschbaselitz	160	COL
7.791	51.252	4712	Werdohl;Broshajen	375	TLG
11.630	51.173	SP15	Dietrichsroda	290	SSA
10.442	50.698	SP19	Grumbach	460	SSA
13.269	50.661	173	Ansprung	700	SSA
9.548	50.574	5423	Oberbimbach_Gemeindsberg	303	GTT
12.643	50.488	SP20	Sosa	690	SSA
6.295	50.270	5703	Radscheid	575	BBZ
12.386	49.919	6040	Wondreb;1	580	GAI
6.879	49.526	6407	Noswendel;Gruenetzberg	309	BBZ
9.795	49.480	6524	Bad_Mergentheim;Galgenberg	337	GAI
11.817	49.445	6536	Gailoh;2	418	GAI
9.743	48.471	7524	Berghuelen;Hohenhuelersteig	743	SHT/FUR
13.240	48.426	7545	Poigham;2	427	GAI/FUR
8.636	48.328	7617	Wittershausen;Atrach	554	SHT
12.853	47.727	8243	Karlstein;4	550	FUR
7.638	47.621	8311	Oetlingen;Signal	454	SHT
9.691	47.578	8424	Lindau;Aeschach_4	493	SHT/FUR
9.073	53.743	WNG	Wingst Observatory	50	---
12.675	52.072	NGK	Niemegk Observatory	78	---
11.277	48.165	FUR	Fürstenfeldbruck Observatoy	572	---

Table 7: Survey Results Reduced to 1999.5

Longitude	Latitude	H [nT]	D [°]	Z [nT]	F [nT]	I [°]	X [nT]	Y [nT]
8.417	55.036	17489	-0.629	46388	49576	69.343	17488	-192
9.984	54.669	17567	0.604	46155	49385	69.163	17566	185
13.367	54.652	17582	1.647	46520	49731	69.296	17575	505
11.225	54.471	17618	0.626	46129	49379	69.097	17617	192
12.847	54.312	17724	1.259	46072	49364	68.958	17720	389
7.916	54.185	17914	-0.508	45892	49264	68.677	17913	-159
11.068	54.008	17840	0.759	46058	49392	68.827	17839	236
13.730	53.962	17916	1.882	46153	49508	68.785	17906	588
12.047	53.910	17901	0.831	45852	49222	68.674	17899	259
6.744	53.596	18104	-0.761	45534	49001	68.317	18103	-240
14.147	53.537	18161	1.852	45789	49259	68.365	18152	587
11.142	53.350	18247	0.651	45605	49120	68.194	18245	207
8.541	53.337	18217	-0.251	45442	48958	68.155	18217	-80
13.342	53.152	18272	1.421	45569	49096	68.150	18267	453
12.107	53.025	18384	1.177	45694	49254	68.084	18380	378
9.794	52.958	18437	(-0.046)	45319	48926	67.862	(18437)	(15)
6.949	52.615	18578	-0.546	45022	48705	67.577	18577	-177
6.838	52.623	18577	-0.633	45025	48707	67.580	18576	-205
11.197	52.555	18564	0.667	45215	48878	67.678	18563	216
14.368	52.490	18550	1.829	45376	49021	67.765	18541	592
8.743	52.438	18643	-0.089	45070	48774	67.528	18643	-29
7.870	52.013	18917	-0.253	44793	48624	67.105	18917	-83
11.438	51.877	18888	0.917	44911	48721	67.189	18886	302
6.071	51.829	19009	-0.899	44597	48479	66.914	19007	-298
10.351	51.795	18952	0.594	44798	48642	67.068	18951	196
10.045	51.531	19082	0.519	44646	48553	66.858	19081	173
13.025	51.298	19020	1.576	44756	48630	66.976	19013	523
14.163	51.285	19101	1.562	44847	48745	66.930	19094	521
7.791	51.252	19266	-0.334	44425	48423	66.555	19266	-112
11.630	51.173	19321	1.711	45508	49440	66.995	19313	577
10.442	50.698	19521	0.706	44439	48537	66.285	19519	240
13.269	50.661	19541	1.519	44433	48540	66.261	19534	518
9.548	50.574	19586	0.406	44164	48312	66.083	19586	139
12.643	50.488	19557	1.256	44266	48394	66.164	19553	429
6.295	50.270	19829	-0.993	43869	48142	65.676	19826	-344
12.386	49.919	19915	1.194	43973	48272	65.634	19911	415
6.879	49.526	20158	-0.508	43474	47920	65.124	20157	-179
9.795	49.480	20263	0.392	43698	48168	65.123	20262	139
11.817	49.445	20149	0.999	43692	48114	65.243	20146	351
9.743	48.471	20694	0.521	43050	47765	64.326	20693	188
13.240	48.426	20653	1.449	43256	47934	64.477	20647	522
8.636	48.328	20781	0.087	42886	47656	64.147	20781	32
12.853	47.727	21004	1.409	42928	47791	63.928	20998	516
7.638	47.621	21188	-0.223	42459	47452	63.480	21188	-82
9.691	47.578	21163	0.469	42459	47441	63.507	21162	173
9.073	53.743	18063	0.133	45651	49094	68.412	18063	42
12.675	52.072	18780	1.277	45059	48816	67.374	18776	419
11.277	48.165	20826	0.904	42954	47736	64.134	20823	329

Table 8: Survey Results (Differences to NGK)

				1999			2000	
Longitude	Latitude	Stat. Nr	H [nT]	D [min]	Z [nT]	H [nT]	D [min]	Z [nT]
8.417	55.036	916				-1286.3	-114.4	1329.3
9.984	54.669	1325				-1208.8	-40.4	1095.8
13.367	54.652	SP1	-1193.5	22.2	1460.5			
11.225	54.471	1533	-1157.5	-39.1	1070.0			
12.847	54.312	SP2	-1051.5	-1.1	1013.1			
7.916	54.185	1813				-861.7	-107.1	833.0
11.068	54.008	SP3	-935.4	-31.1	998.9	-937.4	-30.1	1000.1
13.730	53.962	SP5	-859.6	36.3	1094.0			
12.047	53.910	SP4	-874.7	-26.8	792.5			
6.744	53.596	2306				-671.3	-122.3	475.0
14.147	53.537	SP7	-614.3	34.5	730.1			
11.142	53.350	SP8	-529.0	-37.6	545.9			
8.541	53.337	2617				-558.5	-136.8	383.2
13.342	53.152	SP9	-503.1	8.6	509.7			
12.107	53.025	SP10	-391.6	-6.0	635.0			
9.794	52.958	3024				-338.1	(-73.9)	260.1
6.949	52.615	3307				-197.4	-109.4	-36.7
6.838	52.623	3307n				-198.8	-114.6	-33.8
11.197	52.555	SP11	-211.3	-36.6	156.0			
14.368	52.490	SP12	-225.3	33.1	316.6			
8.743	52.438	3518				-132.8	-82.0	11.3
7.870	52.013	4012				141.6	-91.8	-265.8
11.438	51.877	SP14				108.2	-21.6	-148.6
6.071	51.829	4102				233.9	-130.6	-462.5
10.351	51.795	4228				172.1	-41.0	-261.6
10.045	51.531	4425				301.5	-45.5	-413.2
13.025	51.298	124				244.3	17.9	-302.9
14.163	51.285	SP16				325.3	17.1	-212.0
7.791	51.252	4712				490.8	-96.7	-634.0
11.630	51.173	SP15	545.7	26.0	448.7			
10.442	50.698	SP19	745.4	-34.3	-620.5			
13.269	50.661	173	765.1	14.5	-626.1			
9.548	50.574	5423				806.1	-52.3	-895.3
12.643	50.488	SP20	781.7	-1.3	-792.7			
6.295	50.270	5703	1053.7	-136.2	-1190.6			
12.386	49.919	6040	1139.9	-5.0	-1086.6			
6.879	49.526	6407	1382.3	-107.1	-1585.5			
9.795	49.480	6524	1487.4	-53.1	-1360.7			
11.817	49.445	6536	1373.3	-16.7	-1366.7			
9.743	48.471	7524	1918.7	-45.4	-2009.4			
13.240	48.426	7545	1877.9	10.3	-1803.3			
8.636	48.328	7617	2005.9	-71.4	-2172.9			
12.853	47.727	8243	2228.6	7.9	-2131.2			
7.638	47.621	8311	2412.4	-90.0	-2600.3			
9.691	47.578	8424	2387.1	-48.5	-2600.2			

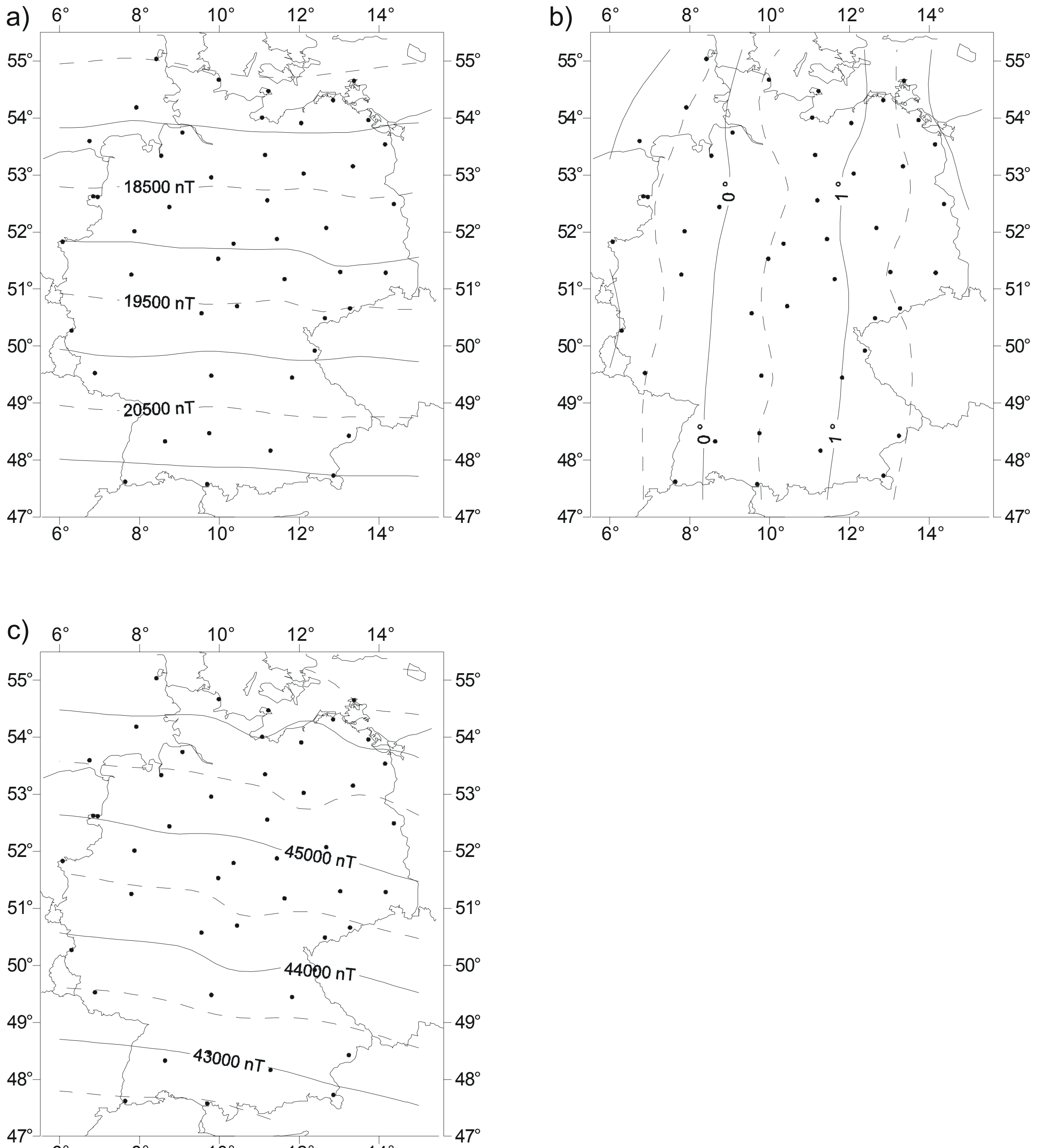

Fig. 4: Magnetic field in Germany 1999.5 as obtained by interpolation of the repeat station network.
a) Horizontal intensity, b) declination, c) vertical intensity.

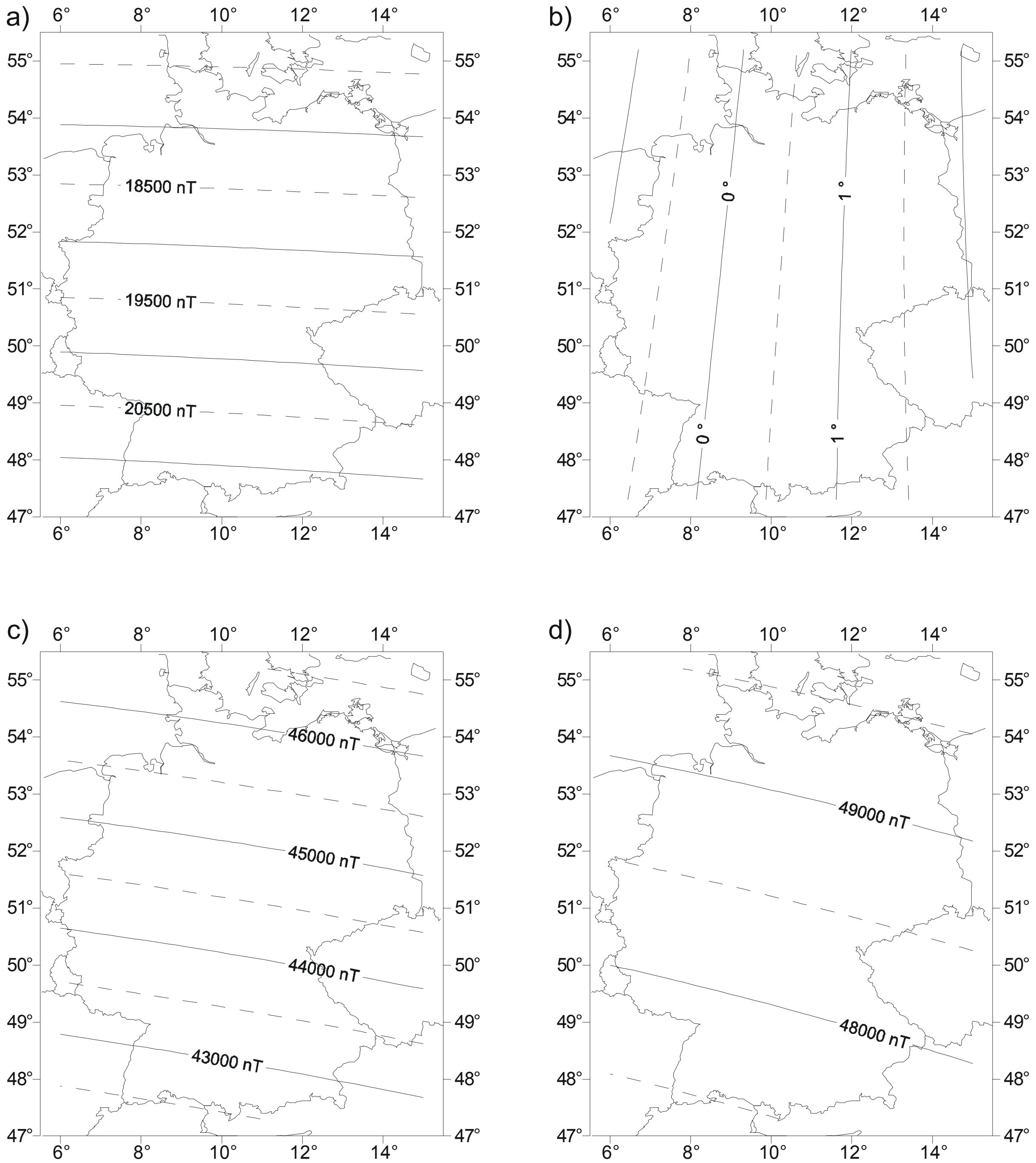

Fig. 5: Second order polynomial normal fields of Germany 1999.5. a) Horizontal intensity, b) declination, c) vertical intensity, d) total intensity

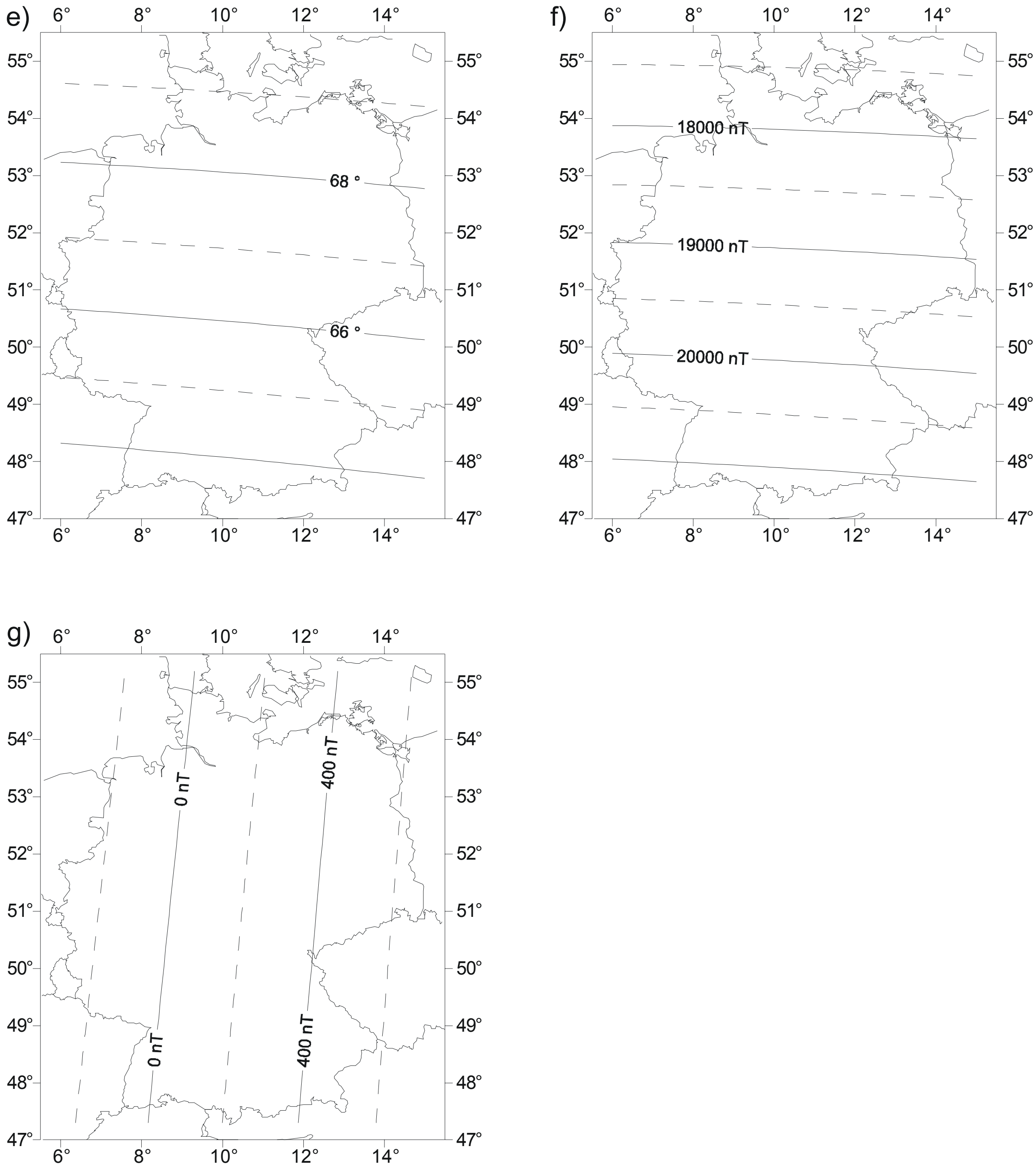

Fig. 5 (cont): Second order polynomial normal fields of Germany 1999.5. e) Inclination, f) north component, g) east component

Table 9: Residuals Between Data and Models

	simple interpolation model		2nd order polynomial model	
	Max. Residual	rms-residual	Max. Residual	rms-residual
ΔH [nT]	-44 / +31	12	-148 / +106	43
ΔD [min]	-2.2/ +3.2	1.4	-18.5 / +19.5	7.7
ΔZ [nT]	-34 / +51	16	-107 / +166	66
ΔF [nT]			-104 / +170	65
Δ I [min]			-8.2 / +10.1	3.1
ΔX [nT]			-149 / +106	43
ΔY [nT]			-92 / +99	39

Table 10: Second Order Polynomial Normal Field Coefficients

Component	a_1	a_2	a_3	a_4	a_5	a_6
H	19881.35	-18.034	-518.840	-0.5241	1.9836	6.5957
D	0.4657	0.31744	-0.03143	-0.001519	0.011312	-0.001576
Z	43885.82	60.828	522.247	0.9418	-2.7191	-5.7630
F	48181.00	47.815	261.063	0.6315	-1.1660	1.8416
I	65.6278	0.04958	0.81894	0.000981	-0.004462	-0.014281
X	19880.83	-18.825	-518.725	-0.84590	2.01042	6.5642
Y	161.7753	110.04055	-14.96756	-0.694806	0.848489	-0.166544

5. Conclusions

The results of repeat station surveys can be improved significantly by using an on-site variometer. Our comparisons show that. provided the measurements are done sufficiently carefully. the accuracy of the measurements itself is much less of a problem for the results than the inhomogeneity of the external and induced part of the magnetic field. Central variometer stations are an improvement on the traditional method using observatories only. However. in regions with high gradients of electrical conductivity such as northern Germany. even this is not enough. However. we must also take into account the accuracy that really is needed. For obtaining interpolated maps of the magnetic components the spatial density of the stations should be good. but an accuracy of several nT will be enough. For detailed studies of secular variation the accuracy has to be better. but we do not expect small scale features here. so a less dense network will do. With the method of central variometer stations we have achieved exactly these aims: a dense network of stations with quite a good accuracy. and additionally a less dense but nevertheless well-distributed network of stations with excellent accuracy. The projected reoccupation interval for the German repeat station surveys now is two years. Due to our experiences with this survey and some practical problems with the locations of the stations the distribution of the variometer stations will change slightly in the next survey. but hopefully will be kept constant for a long time span afterwards.

Acknowledgements

We are grateful to G. Schulz (Wingst observatory), H.-J. Linthe (Niemegk observatory) and M. Beblo (Geophysical Observatory Fürstenfeldbruck) for important contributions regarding the repeat stations and former survey practice. Further, we especially thank W. Poggendorf for his participation in the laborious field work.

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A1 Detailed description of measurements and processing of repeat station data

A1. 1. Measurements

Variometer station

A variometer station consists of the LEMI variometer and a GSM proton magnetometer. The site is checked for magnetically quiet conditions in the same way as the repeat stations. The variometer is buried in the the ground about 40 cm deep and levelled horizontally. It is set up to measure the variations H. D (in nT) and Z. The orientation is achieved by turning it in the direction that D is zero. Orientation errors are not considered in our processing so far. The instrument is fixed by stuffing soil around it. covered by a plate of styrofoam. a cardboard and a layer of soil. Thus it needs some hours (typically about 5 h) to adjust to temperature; subsequently. the sensor temperature variation is few degrees at most. The electronics are kept in an aluminium chest 20 to 50 m away. It is placed in shade. The temperature variations of the electrics are higher than those of the sensor. However. in tests they were shown to have no significant effect on the measurements within the desired temperature range. The sample interval is one second. The proton magnetometer is set up several metres away. The sample interval is set to 10. 12 or 20 seconds.
Absolute measurements at the variometer stations are generally only done once. after the temperature has settled or at the end of the recording.

Repeat station

Most of the stations are marked by nonmagnetic markers. Where this is not the case the descriptions should be accurate enough to relocate the stations with an accuracy better than 1 m. Prior to the measurements the station is rechecked for magnetically quiet conditions. The surroundings are checked visually for changes (new buildings. wires etc.) and total intensity profiles are carried out across the station.
If geodetic north is determined by the gyro-theodolite. these measurements are done previously to the magnetic measurements. The angles to all the reference marks that will be used with the magnetic measurements are taken.
The measured geomagnetic components are F. D and I. For total intensity. a GSM proton magnetometer is used. About 50 values are taken with a sample interval of 5 or 6 seconds directly at the station. at the same position as the subsequent D and I measurements. The fluxgate theodolite is installed and the angles to all available reference marks are taken. Two sets of D and I measurements are taken (D I D I). one set consisting of one measurements in each of the four possible orientations of the fluxgate theodolite. The angles to the reference marks are taken again for control. Finally. another ca. 50 F values are taken directly at the station.
The proton magnetometer is set up several metres from the repeat station to record F at the same sample interval as the one at the variometer station for additional control during the D and I measurements.

A1. 2. Processing of the data

Prior to the processing. all recorded data are checked visually for disturbances and compared to observatory recordings. The comparison of F recorded at the variometer station with that recorded during the measurement can reveal differences in electrical conductivity of the subsurface. if the conditions were not magnetically quiet. At the moment that information can only be used as a hint for problems and to evaluate the results accordingly. However. the variometer stations are not final and the locations will be revised according to such problems showing up in this survey.
As with observatory absolute measurements. the sets of D and I measurements have to be converted to one average momentary value per set. We take 6 values from both F measurements respectively and reduce all these F values. and the D and I values of the first / second set to the time of the first D measurement of that set. using the variations of the nearest variometer station or observatory. With observatory variation recordings. where absolute values and thus values of all components are known. this is straightforward. With recordings at a variometer station. where only variations of H. D (in nT) and Z are known. the following equations approximating the variations of D in minutes of arc. I and F are used:

$$\Delta D(nT) \approx \Delta D(') \, arc1' \, H \qquad (1)$$

$$\Delta I\,(nT) \approx \cos I \;\; \Delta Z - \sin I \;\; \Delta H \qquad \text{and} \qquad \Delta I(nT) \approx \Delta I(') \, arc1' \, F \qquad (2)$$

$$\Delta F \approx \cos I \;\; \Delta H + \sin I \;\; \Delta Z \qquad (3)$$

with $arc1' = \pi / (180*60) = 2.9089 * 10^{-4}$. The equations are derived by differentiation of the relations between the components and may be used for $\Delta F / F << 1$ (Fanselau 1960). The accuracy of the absolute F and I in these equations is not too critical. and the value is approximated from the absolute measurements. The standard computer program used at Niemegk observatory for this task is applied here.

Now we have absolute D. I and F absolute momentary values for the two points of time. from which all other components can be computed. Baseline values for the variometer stations are then computed. Thus absolute values at the repeat station are determined for the whole time span while the variometer was recording.

The computation of final annual mean values at the repeat station is done according to

$$C(x.t_y) = C(x.t_0) - C(O.t_0) + C(O.\ t_y) \qquad (4)$$

where C(x.t) is the value of geomagnetic component C at location x and time t. x being the repeat station. O the observatory. t_0 the time of the observations at repeat station x and t_y the annual mean centred at the desired epoch (e.g. Newitt et al.. 1996).
This step depends on whether a variometer station is used or not. If only observatory recordings are used. then the difference $C(x.t_0) - C(O.t_0)$ is computed for each of the two times t_0. the observatory annual mean is added and the average of these two results is taken as final result. If a variometer is used. then the difference $C(x.t_0) - C(O.t_0)$ is determined as an average of quiet night time values. usually means of 1 to 3 hours after local midnight. depending on the magnetic conditions. A K value at NGK no greater than 1 is taken as reference here. but the recordings are also checked visually.

If in doubt which variometer station or observatory to take for the reduction (e.g. because the variometer station and observatory are at equal distance from the repeat station) the processing is done for all in question. The visual comparison of the F values recorded during the absolute measurements with the recordings at the variometer station or observatory and the stability of the baseline values are taken as criteria for the decision as to which recordings to take for the reduction. Averages of both are taken if this seems sensible.