P-03-60

Forsmark site investigation

QC-report concerning helicopter borne geophysics at Forsmark, Östhammar, Sweden

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December 2003

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Keywords: geophysics, helicopter, magnetometry, electromagnetic, radiometric, data processing, quality control.

Contents

1 Introduction

Helicopterborne geophysical measurements have been performed in the Forsmark area on behalf of SKB during August and September 2002. A method description (SKB MD 211.002) describes specifications for calibrations, tests and data quality for the survey. The Geological Survey of Norway (NGU) was the contractor. Details concerning data tests and calibration routines were presented by NGU in an activity specific quality assurance plan (QAP). Peter Walker (Geophysical Algorithms, Canada) was subcontracted by NGU to carry out data processing and quality control. The survey is presented in a survey report /1/ which also includes pre-survey and a post-survey calibrations, tests and quality controls.

It is common that the client contracts independent quality controllers (QC) during large surveys like the present one. In this case, QC has signed for work carried out and in cases where they have found that the data quality has not been up to specifications, ordered reflights. Sören Byström and Peter Hagthorpe at the Geological Survey of Sweden have been QC:s for navigation, magnetometry and spectrometry, whereas Hans Thunehed at GeoVista AB has been the quality controller for electromagnetic measurements. QC has also assisted SKB regarding prioritisation between data coverage and reflights (see below). It should however be pointed out that the contractor has had the full responsibility for data quality throughout the entire production chain to the final delivery of data.

The time frame available for the survey was limited due to environmental impact and community relation issues. A corresponding survey was also scheduled for the Simpevarp area directly following the Forsmark survey. Technical problems with the helicopter and the survey equipment became evident during the commencement of the survey. This resulted in lack of time at the end of the available survey period. It was therefore not possible to get full data coverage and a number of lines that were out of quality specifications could not be reflown.

2 Quality control

Comments regarding quality control performed by the quality controllers follow below for the different methods. Results are also shown in Figures 2-1 to 2-11 and in Tables 2-1 to 2-3.

2.1 Navigation

Differential GPS and a radar altimeter were used for navigation.

Some survey lines were not up to specifications regarding line separation and altitude. Some of these were due to the pilot's decision regarding flight safety and some were due to sudden wind changes. The area around the power plant has been excluded in the statistics below regarding data coverage. The nominal data coverage is shown in red in Figure 2-1. However, an agreement was made between SKB and NGU to skip the very shortest north-south lines in the westernmost and easternmost part of the area. The data were approved due to lack of time for reflights and since the deviations did not seem to affect the data quality in a serious way.

The control of navigation data has resulted in the following statistics for north-south survey lines:

- Line separation not up to specifications: 10%.
- Altitude not up to specifications: 7%.
- Data coverage: 90% of nominal.

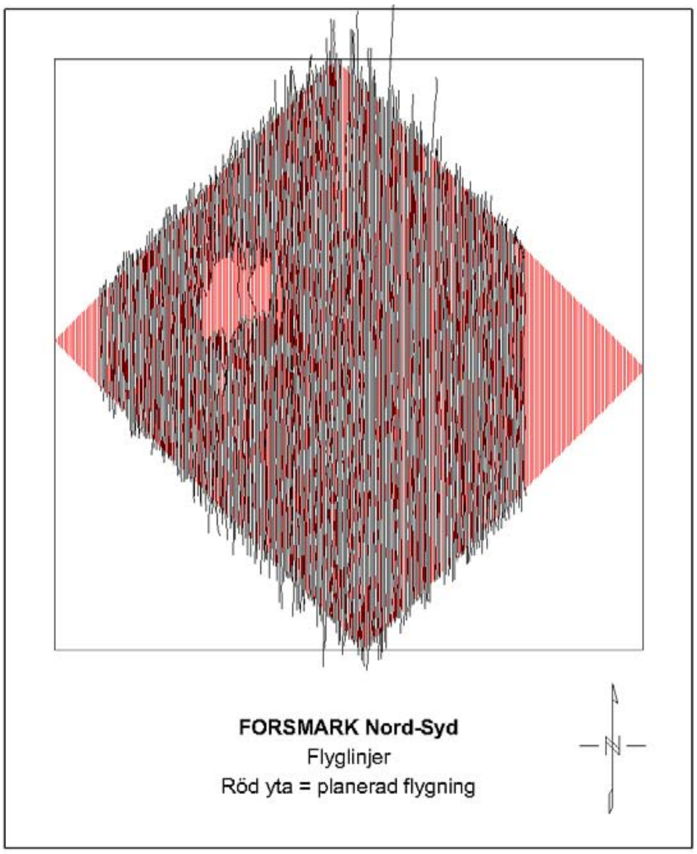

Figure 2-1. *Data coverage, north-south survey lines. The red lines indicate nominal coverage whereas black lines indicate actual coverage.*

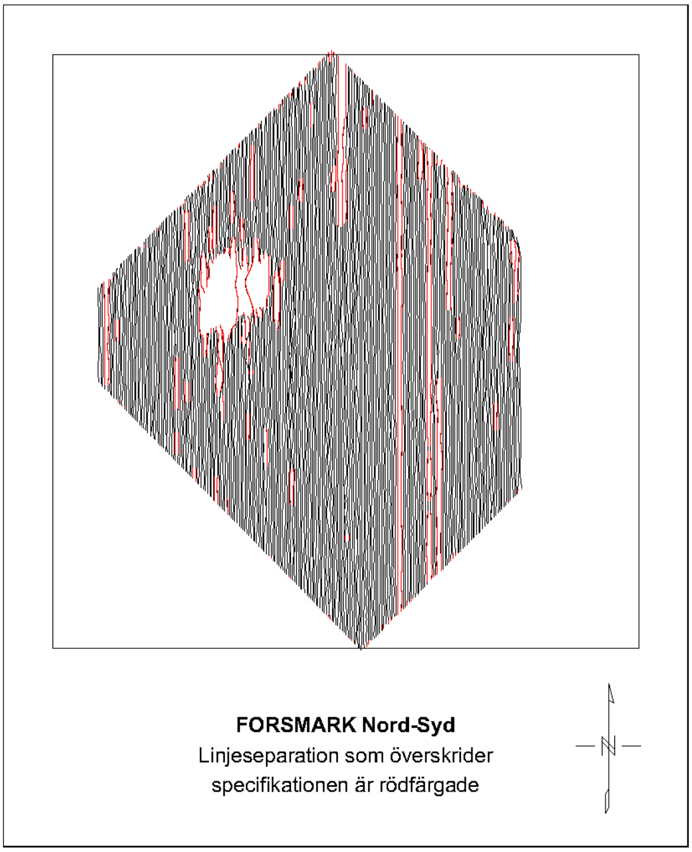

Figure 2-2*. Lines marked with red are those where line separation is out of specification for the north-south survey.*

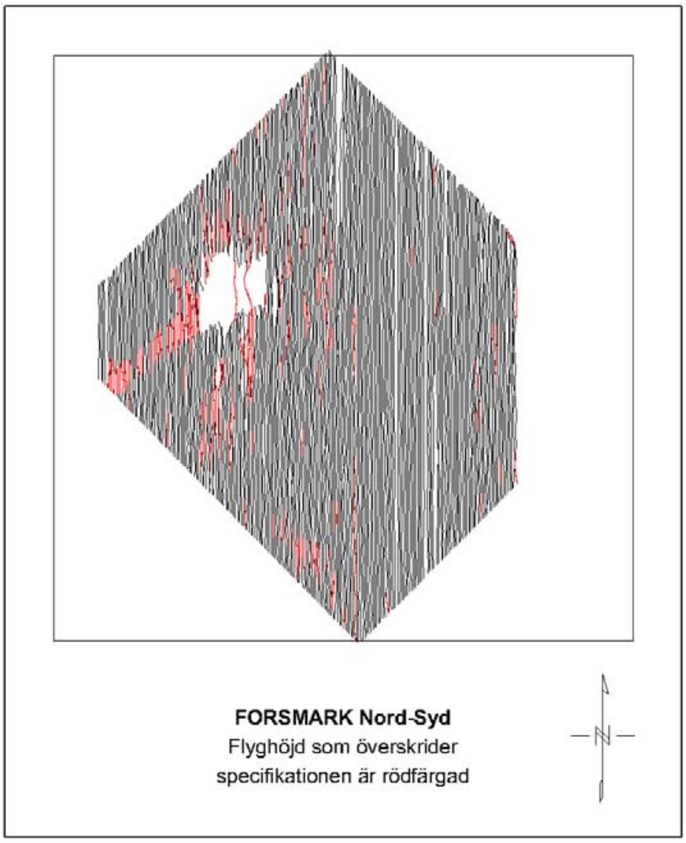

Figure 2-3. *Lines marked with red are those where flight altitude is out of specification for the north-south survey.*

The control of navigation data has resulted in the following statistics for east-west survey lines:

- Line separation not up to specifications: 2%
- Altitude not up to specifications: 6%
- Data coverage: 99.5% of nominal. The power plant area has been excluded in the calculation.

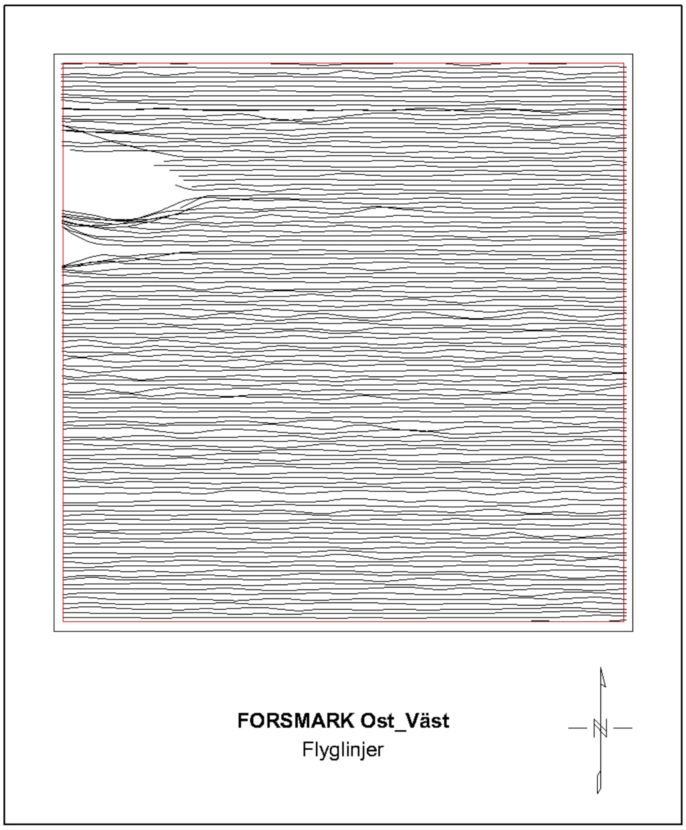

Figure 2-4. *Data coverage, east-west survey lines. The red lines indicate nominal coverage whereas black lines indicate actual coverage.*

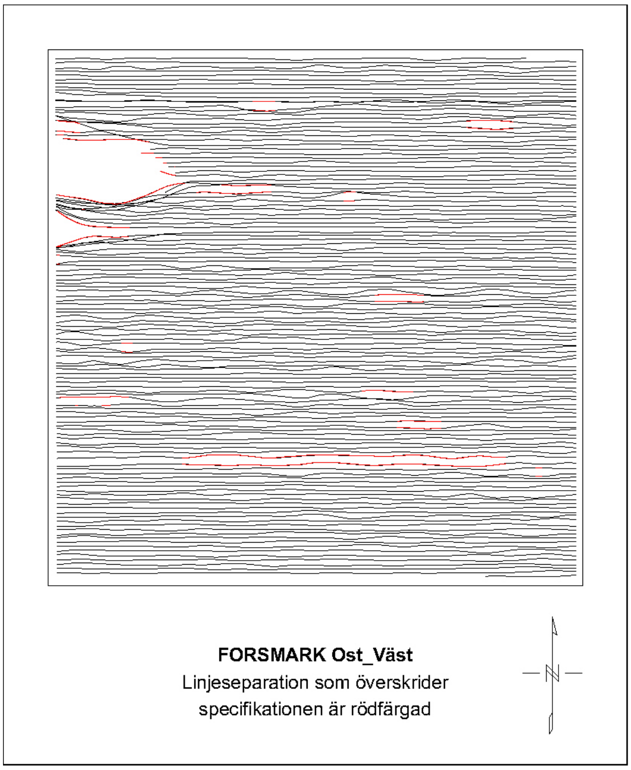

Figure 2-5. *Lines marked with red are those where line separation is out of specification for the east-west survey.*

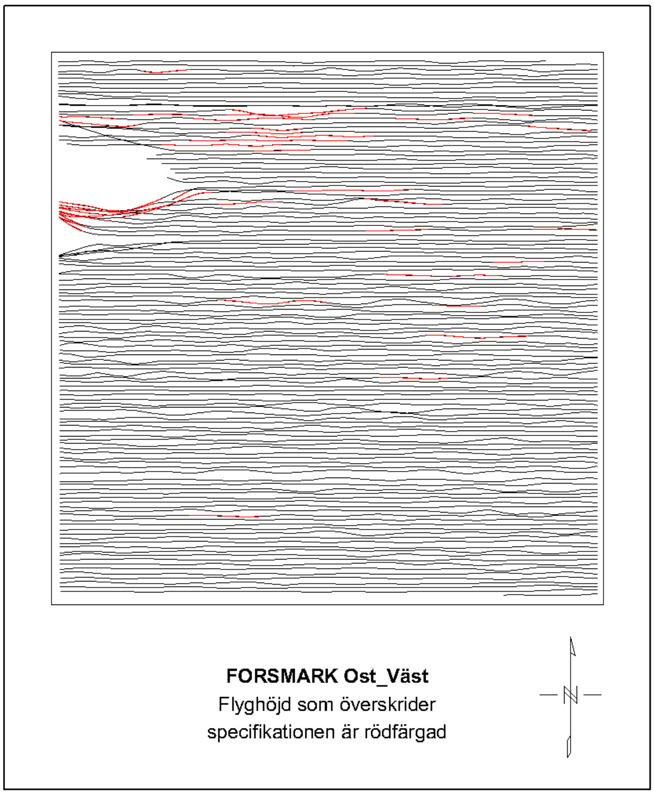

Figure 2-6*. Lines marked with red are those where flight altitude is out of specification for the east-west survey.*

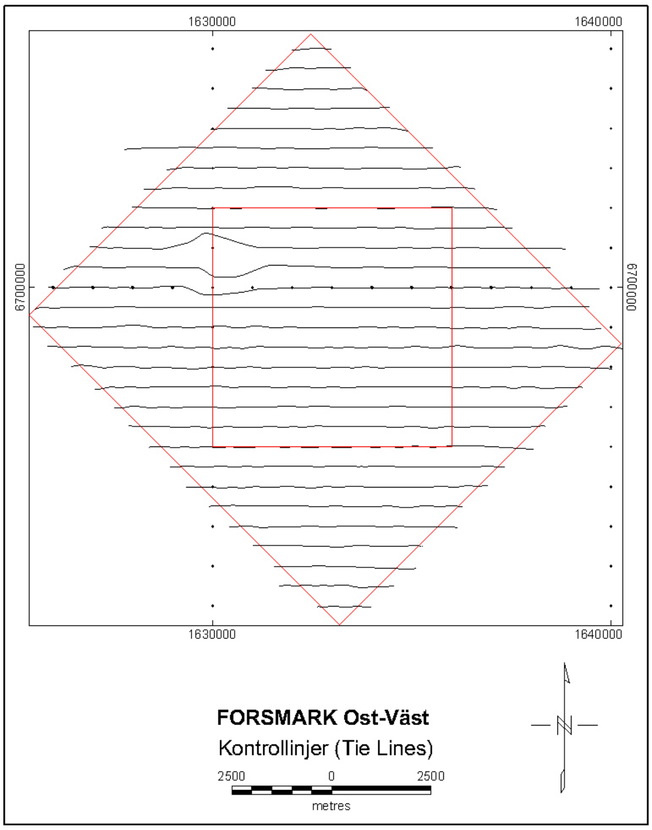

***Figure 2-7**. East-west tie-lines.*

2.2 Magnetometry

Magnetic measurements can be used to map lithological units. The magnetic properties of rocks depend mainly upon the content of magnetite.

The instrument that has been used for magnetic measurements, an optically pumped magnetometer, can be regarded as without drift or scale errors, at least for practical purposes.

The quality of the survey is within the specifications in the method description.

Figures 2-8 and 2-9 show the result of the quality control of the magnetic survey and of diurnal variations.

Some notes about the result of the quality control of the magnetic data:

- An area around the power plant could not be surveyed due to security reasons (see Section 2.1).
- Data coverage is not complete (see Section 2.1).
- A problem with synchronisation of the clocks in the data logging system resulted in an unacceptable uncertainty in the position of the survey points. This problem was later corrected by the contractor and the data in the final delivery are within specifications.
- Survey data were severely affected by a DC power line running from Forsmark to Finland. However, the contractor is not responsible for this effect and the data were approved in spite of this problem.

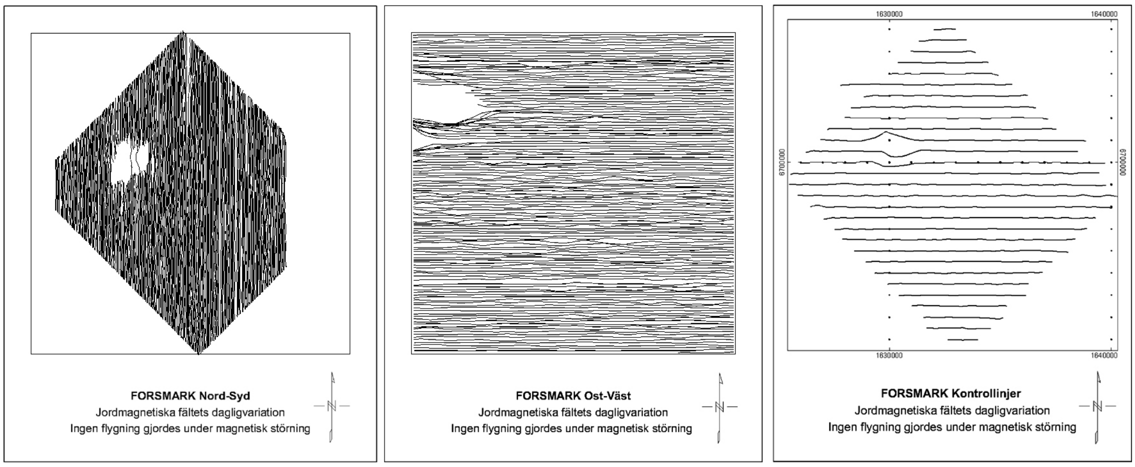

Figure 2-8. *Quality control of diurnal variations. All lines are within specifications (black).*

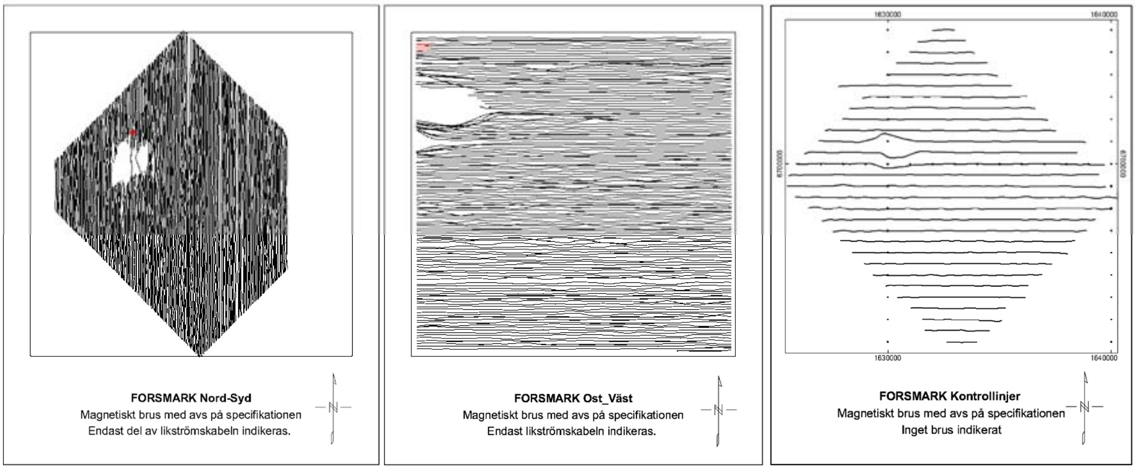

Figure 2-9. *Quality control of magnetometer noise. All lines are within specifications (black).*

2.2.1 Effects of the DC power line between Forsmark and Finland

The magnetic measurements were affected by a DC power line between Forsmark and Finland. It had not been foreseen that this effect should be so large that it made it impossible to locate the base station magnetometer within the survey area.

SGU and GeoVista staff performed tests with a separate base magnetometer at different distances and in different directions from the DC cable and the survey area. The conclusion was that the best alternative would be to use the SGU magnetic observatory at Fiby for acquisition of base station readings. The distance between Fiby and the survey area is approximately 75 to 80 km, i.e. more than the maximum distance of 50 km specified in the method description. After extensive testing, comparisons and considerations it was concluded that the Fiby alternative was superior in quality compared to any available alternative within the specified 50 km radius. Quality control of the base station readings did not reveal any data out of specifications regarding the noise level or diurnal variations.

SGU has performed the necessary corrections on the magnetic data for the effect of the current in the DC cable /1, Section B/. The corrected data are out of quality specifications at some places around the sharp magnetic anomaly caused by the cable. However, the data were approved since the cause most likely was the cable and not noise in the magnetometer.

2.3 Spectrometry

Radiometric information is useful for geological mapping since it gives information about the concentrations of the elements potassium, thorium and uranium. The depth of investigation is however only 10 to 20 cm since γ-rays cannot penetrate any thicker layers of rock or soil.

The radiometric measurements in the Forsmark area fulfilled the requirements in the method description. However, the radon correction was apparently not correct everywhere. This type of problem is difficult to relate to specifications in a method description, but those lines that were levelled by SGU after the final delivery were apparently not corrected in a proper way even if it was difficult to point at any formal error. The lines corrected by SGU are 1060, 1070, 1080 and 1090. Other parameters have been checked by taking random samples without any remarks.

2.4 Electromagnetic measurements

Electromagnetic data should be possible to use for identification of lineaments and for inversion to a layered model. Of these two applications, the latter puts heavy demands on the data quality. Problems with data quality can be due to random noise and to drift in the base level, gain and phase of the measurement system. The drift is usually not correlated between different measurement frequencies. Disturbances can also be due to power lines, radio transmitters and other installations. The method description specifies random noise levels and maximum drift estimated from readings at ground effect free altitude (minimum 300 metres).

The stability and noise level had been tested by the contractor prior to mobilisation to the survey area. Documentation of these tests can be found in a pre-survey report /1, Section A, Appendix A/. The stability of the phase can also be checked since, as part of every survey flight, a test line was flown over an artificial anomaly source (cable loop). A selection of the test lines has been visually inspected and compared. With one exception, the phase of the system seems to have been stable during the survey but an additional control of test line data should be done prior to any possible inversion of data. During flight 25, the IP2-component (see Table 2-2) had a severe phase error. The result was that weak anomalies were reversed in sign whereas stronger anomalies were not. This effect cannot be corrected for and should have resulted in a reflight, but due to lack of time and since data coverage was considered to be of higher priority, no reflights were carried out.

The electromagnetic data from Forsmark were severely affected by cultural noise. The effect was high amplitude noise in the vicinity of the major power lines but also irregular and frequent level shifts for two of the frequencies (7 kHz coaxial coils, 34 kHz coplanar coils). An example of this can be seen in Figure 2-10. The effect of these disturbances must be removed before any attempt is made to perform inversion of the data. However, since both types of noise can be regarded to be caused by external sources they are not the responsibility of the contractor and the data have therefore been approved.

The external noise sources made it difficult to estimate random noise due to the measurement system. Estimated noise levels are presented for three data sets in Table 2-1. The noise has been calculated as the standard deviation between raw data and data filtered with a 7-point median filter. The histogram of the residuals was trimmed by 1% at each end before the calculation of the standard deviation. The calculations are based on roughly 1000 seconds of data for each of the selected flights. Flight 34 was additionally split into 20-second intervals and the calculations were done for each interval individually. Minimum, maximum and median values of calculated noise for these intervals are presented in the three rightmost columns in Table 2-1. The noise levels are in general well within the specified limits.

During inversion of electromagnetic data it is essential that the zero levels are correctly defined. This is particularly important in highly resistive terrains as the signal strength is expected to be low. Before the survey commenced, NGU pointed out that the specifications in the method description might be difficult to live up to regarding level drift. An agreement was made that data could be approved even if the formal specifications were not met, provided that the drift was linear or possible to fit to e.g. a low-order polynomial with small residuals.

Some information on instrument drift can also be gained from measurements over large, continuous areas of high resistive ground or when the helicopter has raised to higher altitude during approach to a new line. However, at least for some of the measured components it seems clear that there is a systematic altitude dependence in the zero level. This means, for example, that there will be a bias in the data after corrections for instrument drift. This bias must be corrected for before any inversion of the data is attempted.

Whether the data meet the specifications in the method description or not is shown on a flight by flight basis in Table 2-3. The two highest frequencies with co-planar coils are shown individually, whereas the quadrature components for the other three components have been grouped. The quality control of the in-phase components for those three frequencies is not shown in the table since they will have a very small impact on inversion of the data.

Reflights should have been done in those cases where instrument drift cannot be estimated with a satisfactory accuracy. Reflights were, however, not carried out due to lack of time and since data coverage was of higher priority. The profiles in question are listed in Table 2-3 and their positions are shown in Figure 2-11.

Table 2-1. Estimated system noise levels for three different flights. All numbers are in ppm. Channel labels are according to Table 2-2.

	Flight 3	Flight 24	Flight 34	Flight 34 min	Flight 34 max	Flight 34 median
IP1	1.1	1.1	0.4	0.2	1.8	0.3
Q1	1.1	1.2	0.3	0.2	1.5	0.3
IP2	0.6	0.7	0.6	0.1	4.6	0.4
Q2	0.6	0.7	0.6	0.1	3.9	0.3
IP3	1.4	0.2	0.3	0.2	3.2	0.2
Q3	1.4	0.2	0.3	0.2	2.9	0.3
IP4	3.7	0.4	2.1	0.4	15.1	1.0
Q4	3.6	0.4	2.0	0.3	16.1	1.2
IP5	0.8	1.8	0.7	0.2	2.3	0.6
Q5	0.6	1.4	0.6	0.1	2.4	0.5

Table 2-2. Channel labels for electromagnetic data.

Channel	Frequency (Hz)	Coil orientation	Coil separation (m)	Component
IP1	7001	coaxial	6	In-phase
Q1	7001	coaxial	6	Quadrature
IP2	6606	Hor. coplanar	6	In-phase
Q2	6606	Hor. coplanar	6	Quadrature
IP3	980	coaxial	6	In-phase
Q3	980	coaxial	6	Quadrature
IP4	880	Hor. coplanar	6	In-phase
Q4	880	Hor. coplanar	6	Quadrature
IP5	34133	Hor. coplanar	4.2	In-phase
Q5	34133	Hor. coplanar	4.2	Quadrature

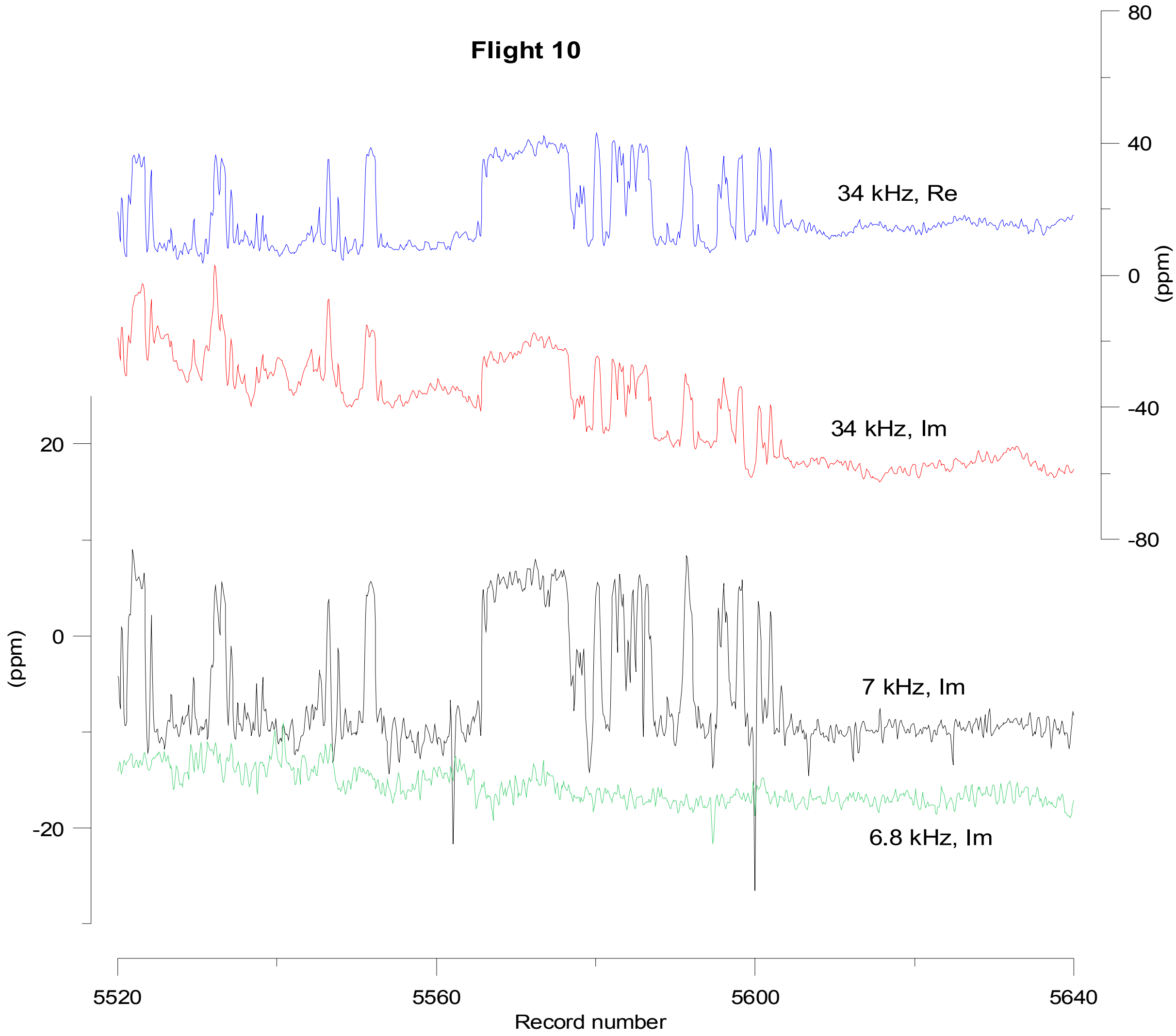

Figure 2-10. *Examples of frequent, irregular level shifts in electromagnetic data. The phenomenon is found for the frequencies 7 kHz (coaxial coils) and 34 kHz (coplanar coils). These data were acquired at ground effect free altitude where only small variations in data are expected. This is also seen in data for the unaffected frequency 6.8 kHz (green curve). The level shifts are correlated between the channels and this might make corrections possible. One record corresponds to 0.1 second.*

Table 2-3. Table showing if level drift is within specifications on a flight by flight basis. An estimation has also been made whether drift corrections can be made with sufficient accuracy even if formal specifications are not met. This is possible if the drift has been linear or gently varying. The two rightmost columns show which profiles should have been reflown if there had been time available. The reason is also specified. The corresponding cells are marked with yellow colour. (N = No, not approved, Y = Yes, approved, ? = Close to specification or difficult to estimate, (Y) = OK, for one or two of the channels but not for the others.

QC EM-data Forsmark 2002, SKB

Flight	Drift Q5 within spec	Drift Q2 within spec	Drift Q5 linear	Drift Q2 linear	Drift IP5 within spec	Drift IP5 linear	Drift IP2 within spec	Drift IP2 linear	Drift Q1,3,4 within spec	Drift Q1,3,4 linear	Reflight recommended	Reason
3	N	Y	N	Y	N	Y	Y?	Y	(Y)	Y	Line 360, 310, 370	Drift Q5
4	N	Y	Y	Y	N	Y	Y	Y	Y	Y		
5	N	Y	N	Y	N	Y	Y	Y	Y	N	550, 620, 560, 630, 570	Drift Q5
6	Y	Y	Y	Y	N	Y?	N	Y	(Y)	Y		
7	N	Y	N	Y	N	Y	Y	Y?	Y	Y	760, 820	Drift and level shifts
8	N	Y	Y	Y	Y	Y	Y?	Y	(Y)	Y		
9	Y	Y	Y?	Y	N	Y	Y	Y	Y	N?		
10	N?	Y	N	Y	N	Y	Y	Y	(Y)	Y	2040, 1920	
11	N	Y	Y	Y	N	Y	Y	Y	(Y)	Y		
12	N	Y	Y	Y	N?	Y	Y	Y	(Y)	Y		
13	N	Y	Y	Y	Y?	Y	Y	Y	(Y)	Y		
14	N	Y	Y	Y	N	Y	Y	Y	Y	Y		
16	N	Y	Y	Y	N	Y	Y	Y	Y	Y		
17	N	Y	Y	Y	N	Y	Y	Y	Y	Y		
18	N	Y	Y	Y	N	Y?	Y	Y	Y	Y		
19	N	Y	Y	Y	N	Y	Y	Y	(Y)	Y		
20	N	Y	Y?	Y	N	Y	Y	Y	Y	Y		

21	N	Y	Y?	Y	N	Y	Y	Y?	N	N?	1230, 1190	Drift and poor nulling IP5, Q5, Q1, Q4
22	N	Y	Y	Y	N	Y	Y	N?	Y	Y		
23	N	Y	N?	Y	N	Y	N	Y	Y	Y	120, 190	Drift Q5
24	N	Y	Y	Y	N	Y	Y	Y	Y	Y		
25	Y	Y	Y?	Y	Y	Y	Y	Y	Y	Y	All profiles	Bad IP2!!
26	N	Y	Y	Y	Y	Y	Y	Y	(Y)	Y		
27	Y?	Y	Y?	Y	N?	Y	Y	Y	Y	Y		
28	N	Y	Y	Y	N	Y	Y	Y	Y	Y		
29	N	Y	Y?	Y	N?	Y	Y	Y	Y	Y		
30	Y?	Y	Y	Y	Y	Y	Y	Y	Y	Y		
31	Y?	Y	Y	Y	Y	Y	Y	Y	Y	Y		
32	N	Y	Y?	Y	Y	Y	Y	Y	Y	Y		
34	N	Y	N	Y	Y	Y	Y	Y	Y	Y	1140, 1090, 1080,1070, 1060	Non-linerar driftQ5
35	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y		
36	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y		
37	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y		

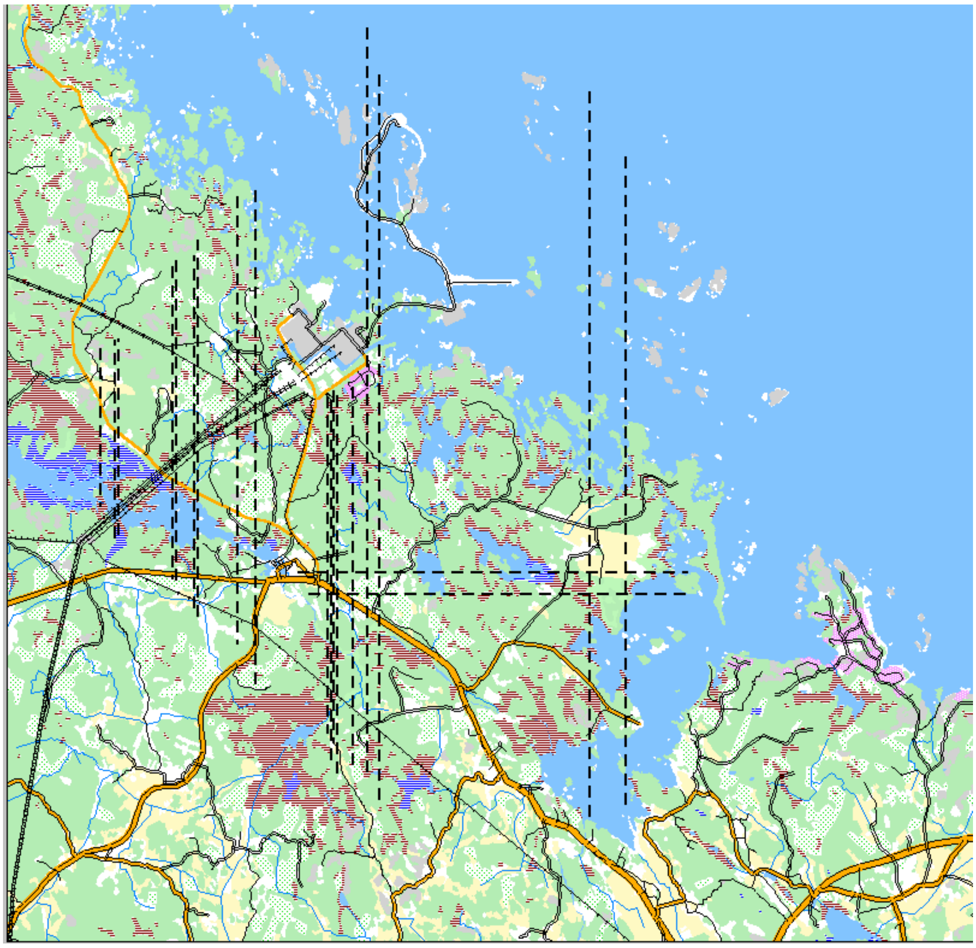

Figure 2-11. *Map showing those profiles (dashed lines) that should have been reflown due to level drift in electromagnetic data. Additionally, the IP2-channel for flight 25 (all east-west tie lines south of RT90 northing 6698500) was not approved.*

2.5 VLF

VLF-measurements were, as required by the survey specification, performed whenever suitable transmitters were transmitting. However, when the VLF-receiver of NGU broke down during the survey period, the survey continued without acquisition of VLF-data until a rented receiver arrived. Therefore, the VLF data coverage is a little bit more limited compared to the other methods. This affects the westernmost part of the surveyed area and a corridor north of the power plant. Although most of the data were collected for the GBR and NAA transmitters some flights have data for alternative transmitters since the VLF-transmitters are turned on and off without notice. No special quality control has been performed on VLF-data.

3 References

/1/ **Rønning H J S, Kihle O, Mogaard J O, Walker P, Shomali H, Hagthorpe P, Byström S, Lindberg H, Thunehed H, 2003.** Helicopter borne geophysics at Forsmark, Östhammar, Sweden. SKB P-03-41. Svensk Kärnbränslehantering AB.