SkyTEM Survey Mo i Rana, Area4 - Norway

Data report

January 2008

SkyTEM Aps

Data Report - Mo i Rana

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"Data report, Mo i Rana" covers data acquisition of a time domain electromagnetic survey carried out in Mo i Rana, Area4 - Norway 2007, by SkyTEM ApS.

Contact person at SkyTEM: Rasmus Teilmann Tel. +45 8620 2050
Email: rasmus.teilmann@skytem.com

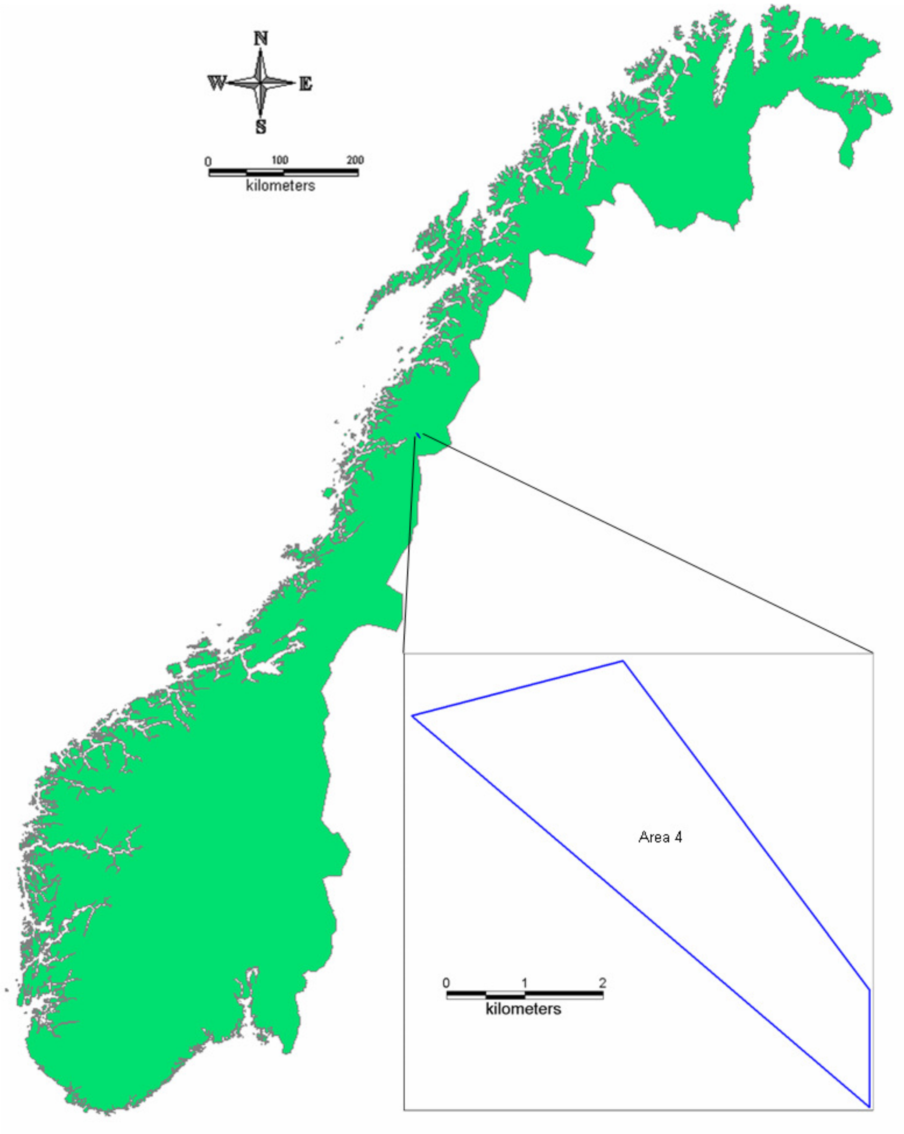


Figure 1. Project overview. The blue box represents the outline of the survey area.

Introduction

On the 7th of september 2007 a time domain electromagnetic survey was performed by SkyTEM ApS in Mo i Rana, Area4 - Norway, Figure 1.

The survey requested by MoMin AS was planned to be 100.6 km of flight lines in total.

SkyTEM has agreed to deliver the electromagnetic raw data measured during the flights together with the standard SkyTEM processing.

The report does not include any geological interpretations of the geophysical dataset.

Client		MoMin AS Postboks 500 8601 Mo I Rana Norway
Field crew		Thomas Bojer, Solvej Trautner Max Halkjær
Field work		the 7th of september 2007
Actually flown line km		100.6
Flight operation	Helicopter type	Eurocopter Astar 350 B2, operated by West Helicopter
	Average flight speed	60 km/h
	Nominal flight height	30 m
Pilots		Tomas Rönkvist
Report	Data processing and presentation	TBK RT SPT
Contact Person at SkyTEM		Rasmus Teilmann Email: rasmus.teilmann@skytem.com

Definition of the area

The survey area is defined below by vertex points. The Coordinate system used is UTM (WGS84) Zone 33N.

Area 4 (45 deg Flight line orientation)

Vertex	Easting [m]	Northing [m]
1	475150	7364500
2	477850	7365200
3	481000	7361000
4	481000	7359500
1	475150	7364500

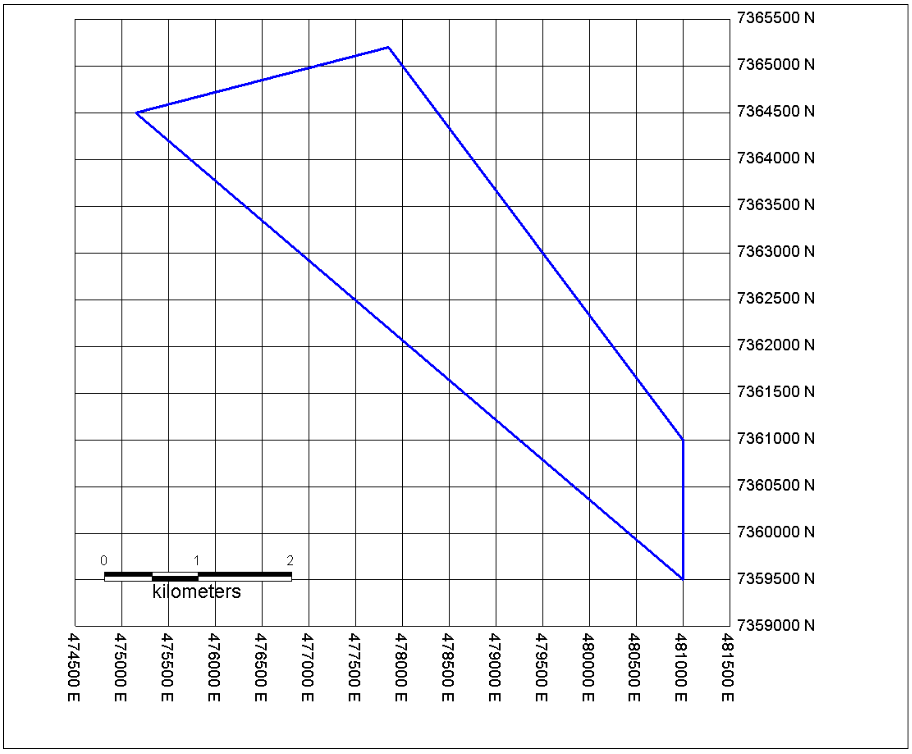


Figure 2. Survey area. Coordinates of the polygon corner points are defined in the table above. UTM (WGS84) Zone 33N.

Instruments and set up parameters

The instrumentation involves a time domain electromagnetic system, inclinometer, altimeters, gps, dgps and a magnetometer.

The measurements were carried out, using a set up as described below.

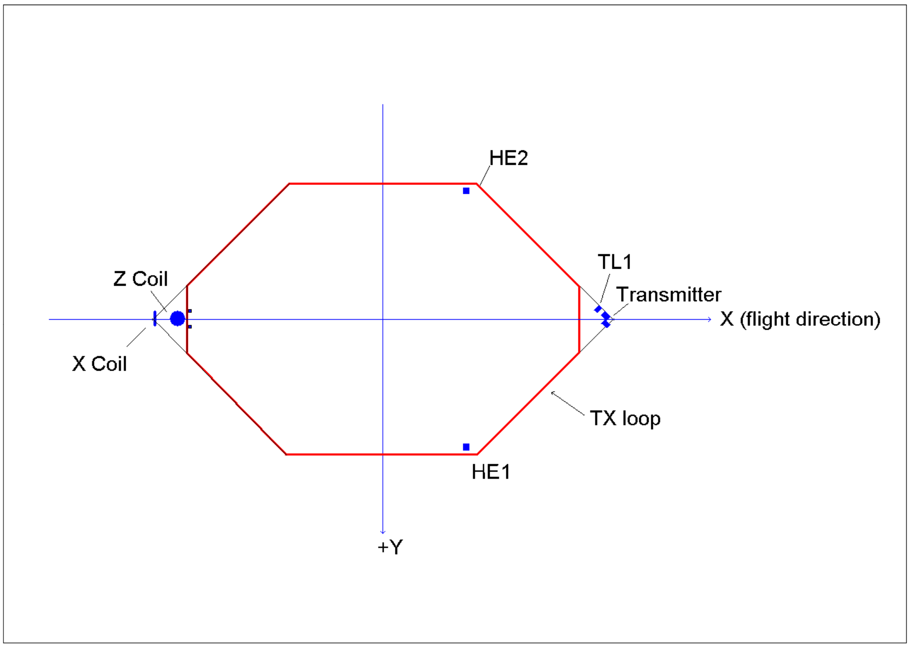


Figure 3. Sketch showing the frame and the position of the basic instruments. The red line defines the transmitter loop. The horizontal plane is defined by (x,y).

The location of instruments in respect to the frame is shown in Figure 3, and is given in (x,y,z) coordinates in the table below.

X and y define the horizontal plane. Z is perpendicular to (x,y). X is positive in the flight direction, y is positive to the right of the flight direction, and z is positive downwards.

The GPS systems are mounted on a box placed 21.3 m above the transmitter together with the two computers used for controlling and collecting data.

The generator used for powering of the transmitter is positioned an additional 2.00 m above the GPS systems.

The DGPS antenna is mounted in the front of the frame.

Device	x	y	z
GP1 (GPS)	12.0	0.0	-21.3
GP2 (GPS)	12.0	0.0	-21.3
DGPS	13.75	0.0	0.00
HE1 (altim.)	5.04	7.77	0.00
HE2 (altim.)	5.04	-7.77	0.00
Inclinometer	13.00	-0.60	0.00
Mag sensor	12.5	0.00	-17.5
RX (Z Coil)	-12.40	0.00	-2.22
RX (X Coil)	-13.75	0.00	0.00
TX (transmit.)	13.47	-0.23	0.00

The location of instruments. See Figure 3.

Transmitter

The time domain transmitter loop can be described as an octagon with the corners listed below:

x	Y
-11.87	-2.03
-5.68	-8.22
5.68	-8.22
11.87	-2.03
11.87	2.02
5.68	8.22
-5.68	8.22
-11.87	2.03

The total area of the transmitter coil defined by the corner points is 314 m^2 and 65.9 m in circumference.

The key parameters defining the transmitter set up are:

Parameter	Value
Number of transmitter turns	4
Transmitter area	314 m^2
Peak current	~ 110 A
Peak moment	140000 Am^2
Repetition frequency	25 Hz
On-time	10000 µs
Off-time	10000 µs
Duty cycle	50%
Wave form	Square
Turn on wave form exp. decay constant	360 s^{-1}
Turn off linear ramp	3.13E+06 A/s
Turn off current end avalanche mode	1.71 A at 32.0 µs
Turn off free decay exp. decay constant	1.0E+06 1/s from 32.0 µs

The measured transmitter wave form can be seen in Figure 13 *and* Figure 14.

Figure 4. The 314 m² frame in production mode.

Receiver system

The decay of the secondary magnetic field is measured using two independent active induction coils. The Z coil is the vertical component, and the X coil is the horizontal in-line component. Each coil has an effective receiver area of 31.4 m^2.

The receiver coils are placed in a null-position:

Z coil (x,y,z) = (-12.40, 0.00, -2.22)
X coil (x,y,z) = (-13.75, 0.00, 0.00)

In the null-position, the primary field is damped with a factor of 0.005.

The Z-component receiver terrain clearance is nominal 32.22 m, and is placed -12.40 m behind the center of the transmitter loop.

The X-component receiver terrain clearance is nominal 30.00 m, and is placed -13.75 m behind the center of the transmitter loop.

Figure 5. Rudder containing the Z coil located approximately 2.22 m above the transmitter coil.

The key parameters defining the receiver set up are:

Receiver parameters	
Sample rate	All decays are measured
Number of output windows	30
Receiver coil low pass filter	450 kHz
Receiver instrument low pass filter	Ch0: 106 kHz, Ch1: 50.5kHz
Repetition frequency	25 Hz
Front gate	46.0 µs

Receiver window times are measured from the start of the transmitter current turn-off. The window times represent the interval from 0.053 ms to 10 ms. A complete list describing open/close and window center times are listed in Appendix 1.

Inclination

Instrument type: Bjerre Technology

The inclination of the frame is measured 2 times per second in two directions. The protractor is placed in the front of the frame.

The angle data are stored as x, y. X is parallel to the flight direction and positive when the front of the frame is above horizontal. Y is perpendicular to the flight direction and positive when the right side of the frame is above horizontal.

The angle is given with one decimal.

The angle is checked and calibrated manually within 0.5 degree by use of a level meter.

GPS

Instrument type: GPS1 and GPS2: Hollux

The geographical coordinates are measured with two independent GPS receivers (GP1 and GP2). The GPS receivers are placed on the top of the box, below the motor generator.

Each GPS delivers one dataset per second. The coordinates are given in Latitude/longitude, WGS84.

The uncertainty in the xy-directions is in the range of ± 10 m.

GPS parameters	
Sample rate	1 Hz
Uncertainty	± 10 m
Coordinate system	Latitude/longitude, WGS84

DGPS

Instrument type:

Chipset: Ublox RCB-LJ 16-channel ANTARIS technology, 4 Hz position update rate.

Antenna: Trimble, Bullet III GPS Antenna

The differential GPS receiver is on top of the cooling unit in front of the frame.

The DGPS delivers one dataset per second. The coordinates are given in latitude/longitude, WGS84.

The uncertainty in the xyz-directions is better than ± 1 m after processing.
The processed DGPS data is combined with the EM data in the xyz-files, giving the precise position.

DGPS parameters	
Sample rate	4 Hz
Uncertainty	± 1 m
Coordinate system	latitude/longitude, WGS84

Altimeter

Instrument type: MDL ILM300R

Two independent laser units mounted on each side of the frame measure the distance from the frame to the ground, see Figure 3.

Each laser delivers 50 measurements per second, and covers the interval from 1.5 m to approximately 130 m.

Dark surfaces including water surfaces will reduce the reflected signal. Consequently, it may occur that some measurements do not result in useful values default value: 9999.99.

The altimeter measurements are given in meters with two decimals. The uncertainty is 10-30 cm. The lasers are checked as a routine against well defined targets.

Laser parameters	
Sample rate	50 Hz
Uncertainty	10-30 cm
Min/ max range	1.5 m / 130 m
Wave length	905 nm

Magnetometer Airborne unit

Instrument type: Geometrics G822A sensor and Kroum KMAG4 counter

The Geometrics G822A sensor and Kroum KMAG4 counter is a high sensitivity cesium magnetometer. The basics of the sensor is a self-oscillating split-beam Cesium Vapor (non-radioactive) princip, which operates on principles similar to other alkali vapor magnetometers.

The sensitivity of the Geometrics G822A sensor and Kroum KMAG4 counter is stated as <0.0005 nT/√Hz rms. Typically 0.002 nT P-P at a 0.1 second sample rate, combined with absolute accuracy of 3 nT over its full operating range.

The magnetometer is synchronized with the TEM system. When the TEM signal is on the counter is closed. In the TEM off-time the magnetometer data is measured from 100 microseconds until the next TEM pulse is transmitted. The data are averaged and sampled as 50Hz.

Parameter	Value
Sample frequency	50Hz
Accuracy	3 nT
Sensitivity	< <0.0005 nT/√Hz rms. Typically 0.002 nT P-P at a 0.1 second sample rate
Magnetometer on	9900 µs
Magnetometer off	10100 µs

Magnetometer Base station

Instrument type: GEM Systems, Inc., GSM-19

Figure 6. GSM-19 magnetometer used as base station

The GSM-19 is a portable high-sensitivity Overhauser effect magnetometer/.

The GSM-19 is a secondary standard for measurement of the Earth's magnetic field with 0.01 nT resolutions, and 0.2 nT absolute accuracy over its full temperature range.

The base station data are sampled with a 1 Hz frequency.

Parameter	Value
Sample frequency	1 Hz
Accuracy	0.2 nT
Resolution	0.2 nT

Synchronizing the data

All recorded data are marked with a time stamp used to link the different data types.

The time stamp is UTC/GMT. The time stamp format is either

yyyy-mm-dd hh:mm:ss.sss or

Date time value defined as the number of days since 1900-01-01

The second notation is very useful for data presentation along a time axis.

Calibration of the TEM system

The complete TEM equipment has been tested and calibrated at the Danish National Reference Site, the 29th of June 2006
The calibration includes measurements of the transmitter wave form and measurements in different altitudes. Hereby, it has been documented that the instrumentation can reproduce the reference site with the same set of calibration parameters and independent of the flight altitude.

The calibration results in the following parameters:

Shift factor 1.0 (on the raw dB/dt data)

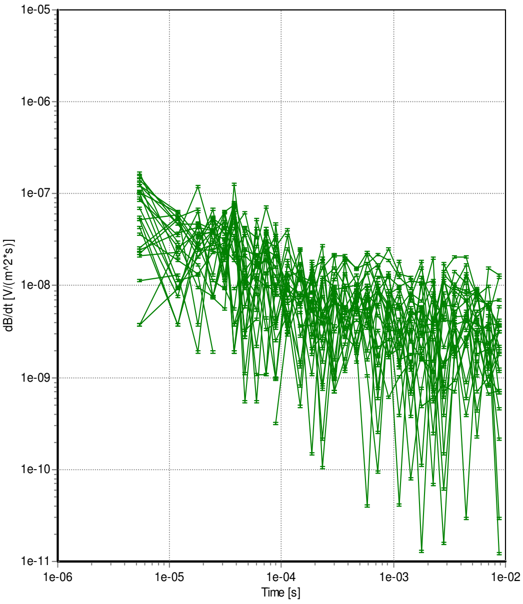
Time shift -1.0 µs

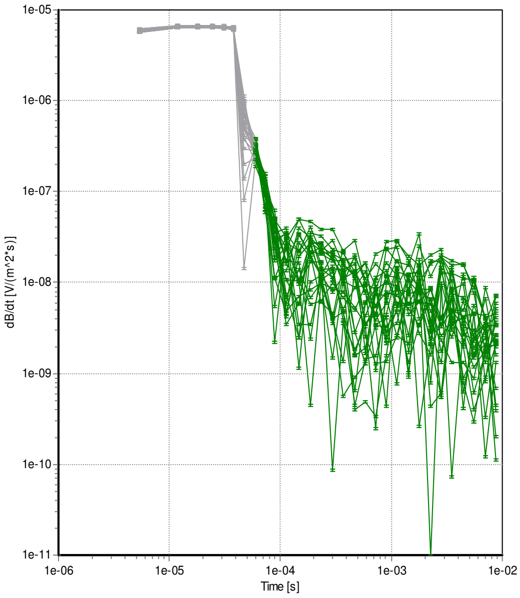
All processed data are corrected according to the calibration parameters.

The wave form as well as the reproduced soundings in different altitudes is shown in Appendix 2.

High altitude test

A high altitude test was performed on the 25th of September 2007 at 1000 m above the ground. The test was performed with exactly the same equipment and configuration used during the project.





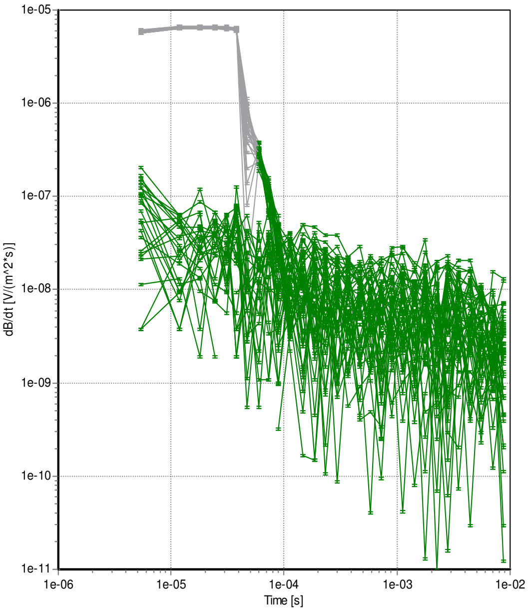


Figure 7. High altitude test performed the 25th of September 2007 1000 m above the ground. A comparison of the back ground noise level (the plot to the left) with the signal when the transmitter is on (the plot to the right). Stack size 96. The figure at the bottom shows the two figures superimposed. The data unit is V/m^2 (data normalized with the receiver coil area only).

The background noise and the signal with the transmitter on is very much alike in the high altitude (Figure 7).

When the transmitter is on, a slightly higher level is seen up to 100 µs. In areas with very low earth signal this may add noise to the early gates

Data Acquisition

The planned flight lines covering the Mo i Rana, Area4 - Norway is shown in Figure 8. The lines are parallel-spaced 125 m apart, with the main area striking 45 deg. Two tie lines crosses the lines perpendicular to the main orientation

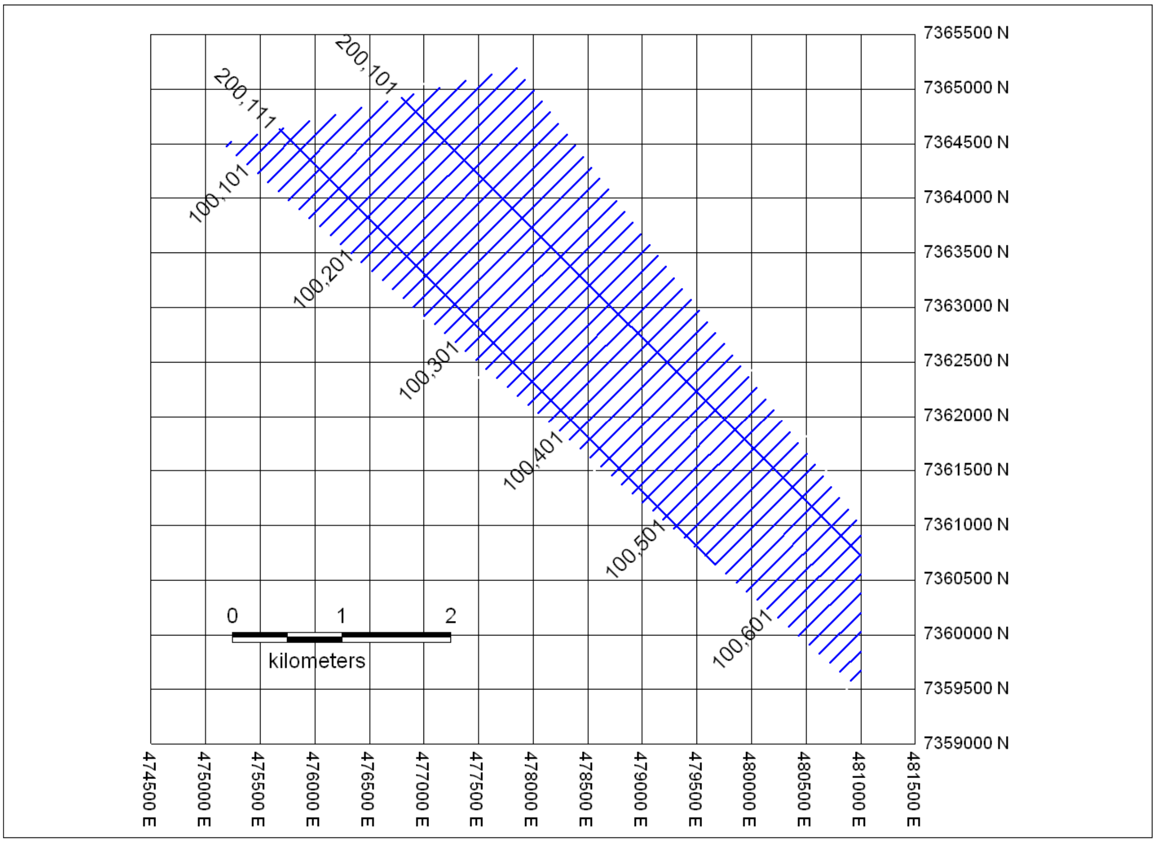


Figure 8. Planned survey lines in the Mo i Rana, Area4 - Norway. Coordinate system UTM (WGS84) Zone 33N.

The flight lines are numbered from 100101 to 200111. A complete list including coordinates and time for begin and end of line can be found in Appendix 3.

The intended terrain clearance is 30.00 m, with an increase over forests, power lines etc. It is always the pilot who desides the safety height for the operation.
The helicopter airspeed was planned to be approximately 60 km/h (17 m/s) above a flat topography, but this may vary in areas of rugged terrain.

Actually flown lines can be seen in Figure 9. Discrepancies from the planned lines occur when possible noise sources are present, or the nature of the ground like roads, buildings and antennas has called for it.

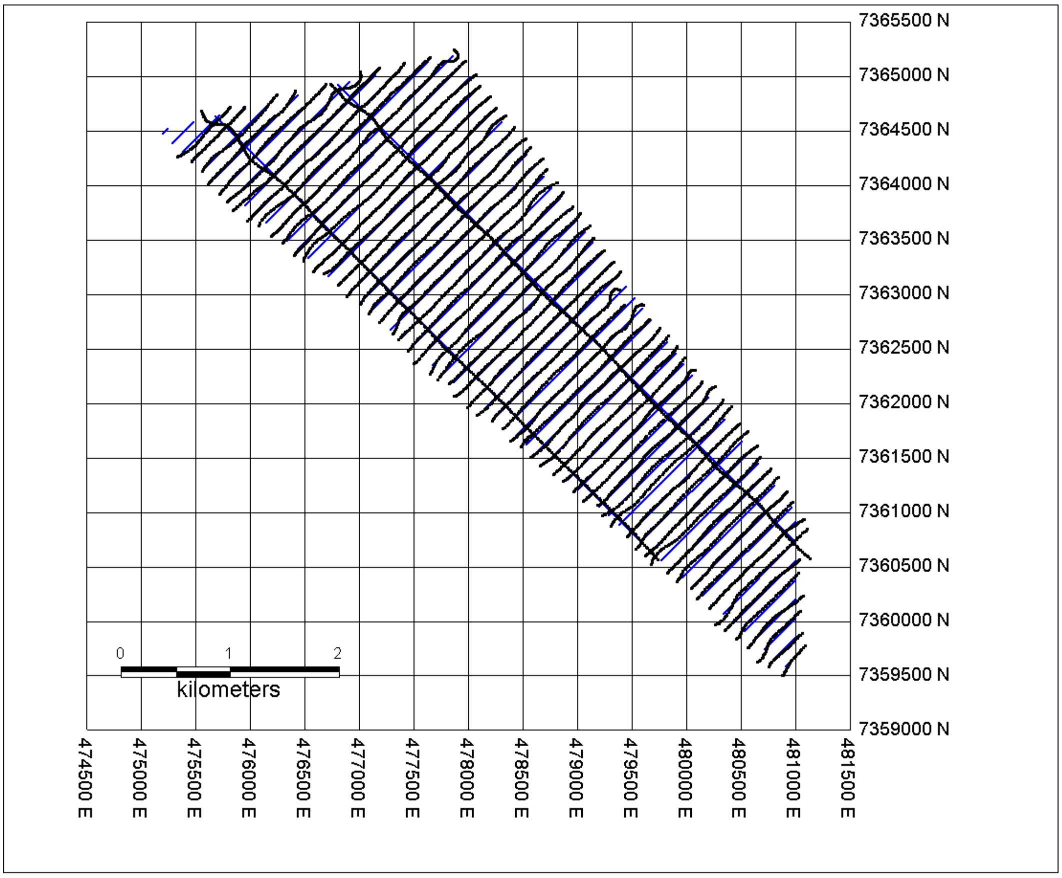


Figure 9. Area A1, black dots represent actually flown lines in respect to planned flight lines (blue lines). Coordinate system UTM (WGS84) Zone 33N.

Flight reports

For each flight, a report with key information regarding the data gathering is made. Listed in the reports are details on the weather, specials data parameters and other events which may influence the data. Selected information from the flight reports are shown in the table below (for all 4 areas):

Date	#Flights	Comments	Weather
20070823	1	Very steep topography in the western part of area1. Steepest part flown on another flight	Light showers, 5m/s W, 10℃
20070824	-	-	Rain
20070825	-	No helicopter on this day	Heavy Rain
20070826	2	Additional PC with background maps installed in the helicopter on request from the pilot	Showers, 5-8m/s SW, 10℃
20070827	3	Few restarts on PaPC (Flight01). Flight continued.	Some low clouds, 5m/s W, Showers
20070828	2	-	Fair, 5m/s W, 15℃
20070829	1	Short return after 3 min. of flight. No problem with the equipment	Overcast, 5-8 m/s W
20070830	-		Bad weather
20070831	2	Some lines flown twice on flight 1 and 2 (No charge)	Showers, 5 m/s W, 2-5℃
20070901	2	PaPC changed. Few drops in Voltage. Data ok.	Showers, 5 m/s, 5-10℃
20070902	1	Flight #2 aborted due to heavy rain	Showers, 5 m/s, 5-10℃
20070903	1	Few drops in Voltage. Data ok.	Showers, 5-8 m/s, 5-10℃
20070904	-	Instrument maintenance, crew change	Heavy Rain
20070905	-	-	Heavy Rain
20070906	1	-	Showers, 10-15 m/s, 5-10℃
20070907	2	Flights in Area 3, Area4	Cloudy, 2-5m/s W, 10-12℃
20070908	2	Flights in Area 1, Area 3	Cloudy, Strong wind ENE
20070909	1	Flights in Area 1	Cloudy, 2-5m/s E, 10℃
20070910	-	Helicopter at service	-
20070911	-	Helicopter at service	-
20070912	-	Helicopter at service	-
20070913	-	Helicopter at service	-
20070914	-	Helicopter at service	-
20070915	-	Helicopter used for other jobs at MoMin	Too strong wind for production
20070916	2	Area 3	2-6 m/s SW, Clouds at 800m
20070917	2	Area 3, Crew change	High Clouds 0-4 m/s NW
20070918	-	-	-
20070919	2	Magnetometer board broke during Take off. System landed and problem fixed before production flight	High Clouds 0-4 m/s
20070920	2	Area 2, NRK Filming SkyTEM	High Clouds 2-4 m/s
20070921	1	Area 2	High Clouds 2-4 m/s, 5℃
20070922	2	Area 2	Clouds at 1200m, 3-5 m/s S.
20070923	2	Area 2, Radio cable snapped during take off.	High Clouds 2-4 m/s S, 5℃
20070924	-	No Production	-

20070925	1	High Altitude test, No Production due to heavy wind	8-12 m/s, No clouds
20070926	-	No Production	-
20070927	3	Area 2	No clouds 0-3 m/s NW, 4℃
20070928	1	Area 2	Few clouds, 1-3 m/s NW, 6℃

Processed data

Selected control parameters are plotted in Appendix 4. The plot contains information about the flight altitude, speed, angle of the frame, transmitted current, transmitter voltage and transmitter temperature.

Average value of control parameters are found in the table below

Control parameter		Value
Ground speed*)		40-80 km/h
Measured height		20-100 m
Processed height		30-70
Tilt angle	X	
	Y	
Tx Voltage**)	Tx_off	66-67 V
	Tx_on	62-34 V
Current**)		108 - 110 A
Tx temperature**)		25-30ºC

**) Actual speed varies as a function of day and flight direction due to different wind directions and magnitude.*
***) Few spikes are seen in the temperature, current and voltage data. These are not caused by errors in the instruments but a matter of digital drop outs.*

XYZ-files

The xyz files are the main results of the SkyTEM survey, containing all the collected EM data and information for the interpretation and inversion.

Based on the positions of all devices a xyz ASCII file is produced. All parameters in the xyz-file hence refer to the Origo of the frame.

The raw EM data are filtered based on the signal level, i.e. high level means a low number of transients in the stack and vice versa.

The xyz file is used as input to the inversion and interpretation software.
The parameter plots are based on the xyz-file.

The projection of the xyz-files is UTM (WGS84) Zone 33N.

Each filtered data set at a given position is numbered with a unique fiducial number.

The header of the xyz-file gives the following information:

Parameter	Typical value	Explanation
Fid	1-178411	Unique Fiducial number
Line	200501	Flight line number
Flight	20070920_Flight01	Name of flight
DateTime	39345.3230111921	DateTime format
Date	2007/09/20	Date yyyymmdd
Time	074508	Time hhmmss
AngleX	2.890	Angle in flight direction [deg]
AngleY	-2.363	Angle perpendicular to AngleX [deg]
Height	36.5	Filtered Height measurement [m]
DTM	576.8	Digital Terrain Model [m.a.sl]
Current	109.95	Current [A]
Mag	0.0	Mag reading –Not active. See separate Magnetometer data file
N	7345887.838	UTM (WGS84) Zone 33N [m]
E	478298.961	UTM (WGS84) Zone 33N [m]
Alt	613.3	DGPS/GPS Altitude [m]
GdSpeed	69.2	Ground Speed [km/t]
2_Z2_8 - 2_Z2_30	7.4402E-013	Normalized Z-coil value: gate 8-30
4_X2_8 – 4X2_30	-2.9481E-012	Normalized X-coil value: gate 8-30

Inversion of the TEM data

In this section, the particulars of modeling and inversion of SkyTEM data from Mo i Rana, Area4 - Norway will be described with reference to the more general material found in Appendix 5.

The inversion code is named SELMA, ref /2/.

The model used for inversion of SkyTEM data is a multi-layer model (MLM) with 30 layers. Thicknesses and layer depths are stated in the table below.

Layer #	Layer Thickness [m]	Layer depth [m]
1	10.00	0.0
2	10.04	10.00
3	10.11	20.04
4	10.22	30.15
5	10.38	40.37
6	10.6	50.8
7	10.8	61.3
8	11.1	72.1
9	11.4	83.2
10	11.7	94.6
11	12.1	106.3
12	12.6	118.5
13	13.1	131.1
14	13.6	144.1
15	14.2	157.8
16	14.9	172.0
17	15.6	186.8
18	16.3	202.4
19	17.2	218.7
20	18.0	235.9
21	19.0	253.9
22	20.0	272.9
23	21.1	293
24	22.3	314.1
25	23.6	336.4
26	24.9	360.0
27	26.4	384.9
28	27.9	411.3
29	29.6	439.2
30	N/A	468.8

The inversion is performed on individual soundings along the profiles. The model is one dimensional.

The input data is the xyz file described in the chapter “Processed data”.

As initial model the resistivity of each layer is set to 200 Ωm, i.e. the initial model is essentially a homogeneous half space. The maximum resistivity is set to 10000 Ωm and the minimum resistivity is 0.01 Ωm.

The only prior information involved is thickness of each layer and a vertical smoothness constraint from layer resistivity to layer resistivity. By using a L_1-norm inversion approach, the final model is characterized by sharp layer boundaries, even though there is a constraint between the resistivities.

Noise model

For the survey, the noise parameters have pragmatically been determined as 0.1ms and 2.5E-13 in field units normalized with Tx moment.

The noise model V is expressed as a sum of two contributions:

$$V = \frac{V_0}{\sqrt{2}} \frac{t_0}{t} \sqrt{1+\frac{t}{t_0}}$$

Where $t_0 =$ 0.1 ms and $V_0 =$2.5E-13 in field units, normalized with Tx moment. See Appendix 5 for more details.

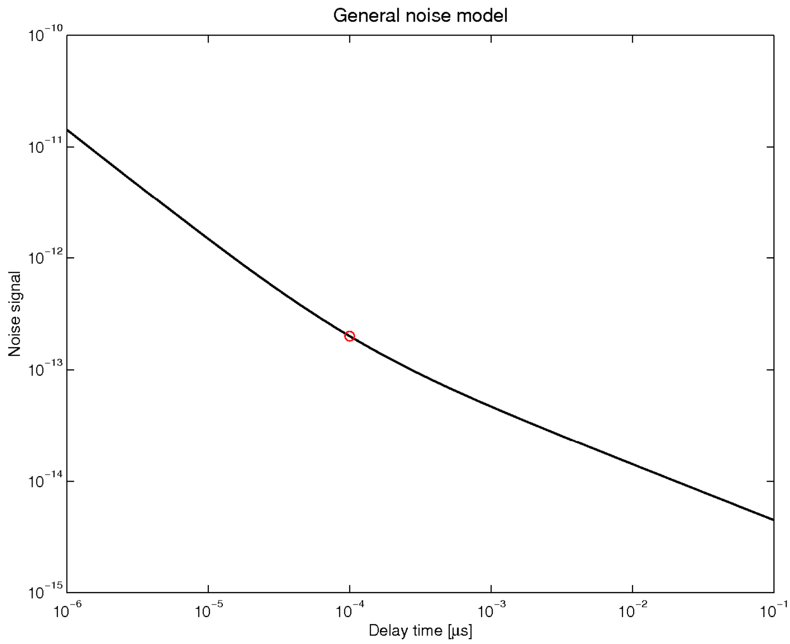


Figure 10. The noise model. The red circle denotes the actual parameters of 0.1ms and 2.5E-13.

The data used for the inversion has not been reviewed to avoid data affected by man made conductors such as power lines, rail roads etc.

Presentations

The models resulting from inversion of the individual sounding data are displayed in model sections/profiles, and interval elevation maps of conductivity and resistivity.

With the conductivity sections the color scale represents variations of the good conductor where as the resistivity presentations result in a more detailed picture of the more poor conductors.

The conductivity and resistivity model sections are enclosed in digital form. A brief description is given in appendix 6

The quality of the inversion results can be evaluated by inspecting the residuals.

The data residual is calculated by comparing the measured data with the signal, which the resulting model would produce. If the residual is in the range of 1, the data are well fitted. If the residual is high, it can be due to two or three dimensionally effects. Another possibility is if the resistivities are high, the signal to noise level will be reduced resulting in more noisy data and a higher residual. In this case it is reliable that the inverted resistivities are high. The last source to a higher residual could be coupling effects to power lines and other man made conductors.

The residual of vertical constraints shows where the model has to diverge from a homogeneous half space in order to fit data. A high residual is an indication of deviation from a 1-D model e.g. in case of a conductive structure.

The total residual is a weighted average of the individual residuals.

Maps of data residual, vertical constraints and total residuals are enclosed in digital form.

The interval elevation maps of conductivity and resistivity are enclosed in digital form. A brief description is given appendix 6

For every 20 m depth an average conductivity and resistivity is calculated, based on the obtained inverted model. The result is depth slices, showing variations in specific depth-intervals.

Similar for every 20 m a horizontal slice is extracted. When looking at the horizontal slice, the map will not show any colors in areas where the topographical terrain is below the actual horizontal slice.

Digital terrain model

The digital terrain model (DTM) is a digitized topographic map of the survey region.

The DTM is generated from measurements of the height and measurements of the DGPS altitude giving the topography as:

DTM = (DGPS_altitude) – (HEIGHT).

The DTM is located in the data delivery catalogue as .tab files.

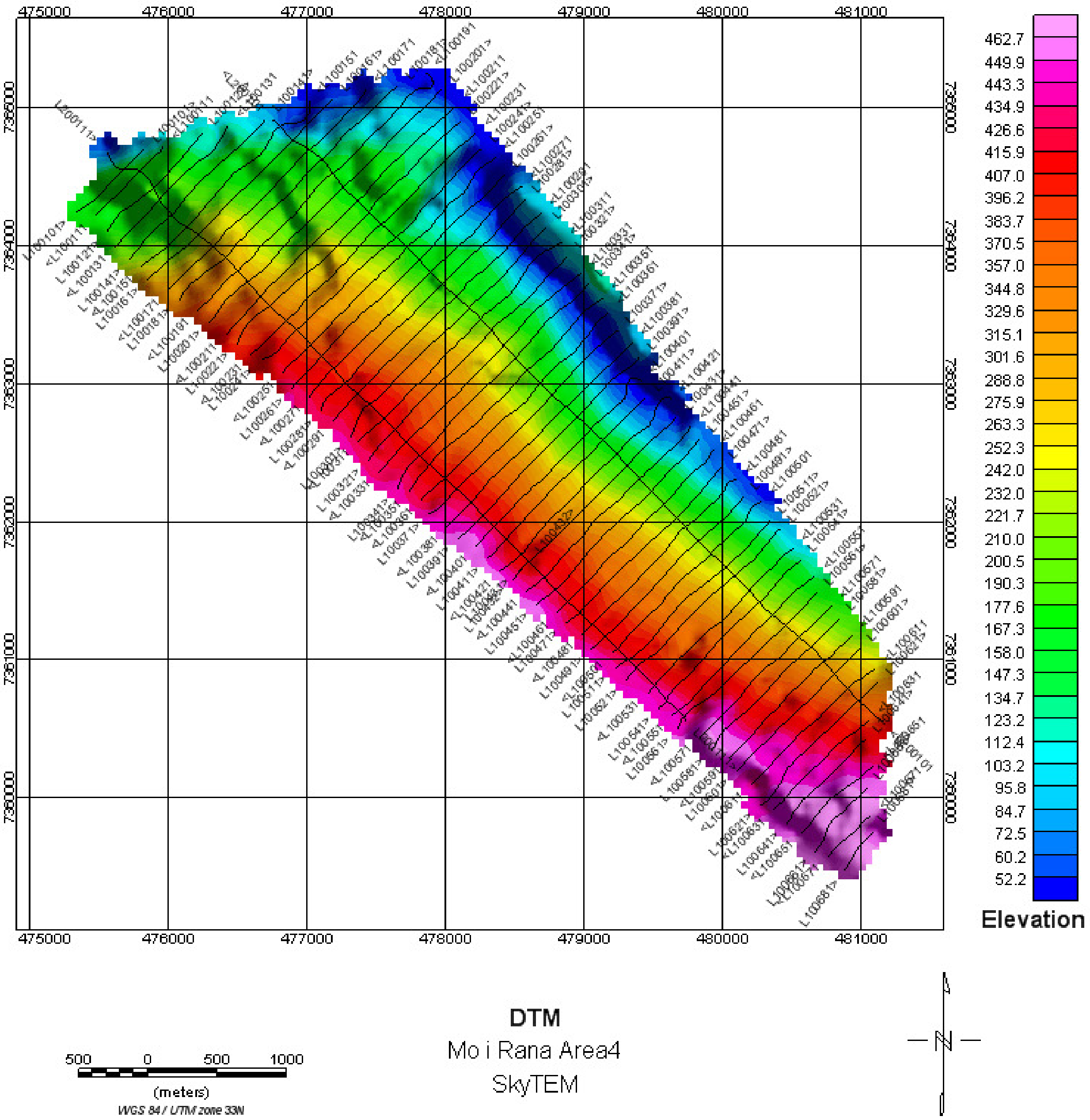


Figure 11. DTM of the Mo i Rana, Area4 - Norway. Meter above sea level. Coordinate system UTM (WGS84) Zone 33N.

Magnetic data

The magnetic data is located in the Datadelivery Catalogue.

Processing of the magnetometer data involves the following steps:

1. Spike removal (non-spike filtering and spline interpolation)
2. Editing and checking of the raw data
3. Base station corrections
4. Since the heading error is very low – <0.15 nT over entire 360 polar and equatorial spin, no heading error correction has been used
5. Gridding and contouring

Figure 12 shows a contoured map after processing data from the magnetometer.

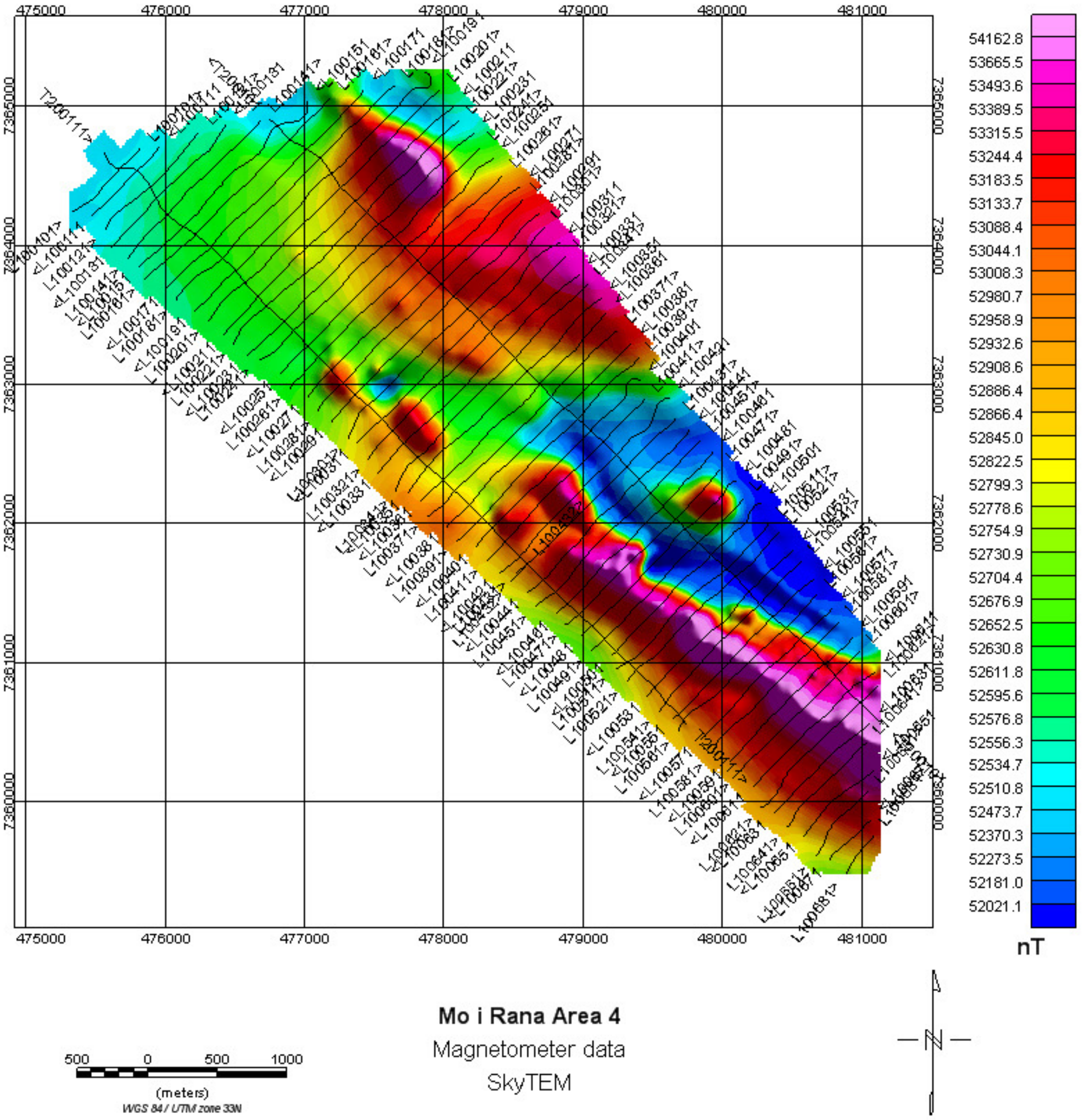


Figure 12. Total magnetic field after correction [nT]. Coordinate system UTM (WGS84) Zone 33N.

References

/1/ Sorensen, K. I. and Auken, E., 2004, SkyTEM - A new high-resolution helicopter transient electromagnetic system: Exploration Geophysics, 35, 191-199.

/2/ Christensen, N. B., 2002. A generic 1-D imaging method for transient electromagnetic data. Geophysics, 67, 438-447.

Appendix

Appendix 1: Time gates

Window	GateOpen	GateCenter	Gatewidth	GateClose	Comment
1	2.66E-06	4.47E-06	3.63E-06	6.29E-06	Not used
2	9.10E-06	1.08E-05	3.63E-06	1.27E-05	Not used
3	1.55E-05	1.72E-05	3.63E-06	1.91E-05	Not used
4	2.19E-05	2.36E-05	3.63E-06	2.55E-05	Not used
5	2.83E-05	3.00E-05	3.63E-06	3.19E-05	Not used
6	3.47E-05	3.64E-05	3.63E-06	3.83E-05	Not used
7	4.09E-05	4.60E-05	1.01E-05	5.10E-05	Not used
8	5.37E-05	5.88E-05	1.01E-05	6.38E-05	
9	6.65E-05	7.16E-05	1.01E-05	7.66E-05	
10	7.93E-05	8.76E-05	1.65E-05	9.58E-05	
11	1.00E-04	1.11E-04	2.12E-05	1.21E-04	
12	1.29E-04	1.45E-04	3.06E-05	1.60E-04	
13	1.65E-04	1.82E-04	3.34E-05	1.98E-04	
14	2.09E-04	2.32E-04	4.70E-05	2.56E-04	
15	2.63E-04	2.92E-04	5.66E-05	3.20E-04	
16	3.30E-04	3.70E-04	7.90E-05	4.09E-04	
17	4.14E-04	4.63E-04	9.78E-05	5.12E-04	
18	5.18E-04	5.79E-04	1.22E-04	6.40E-04	
19	6.48E-04	7.27E-04	1.58E-04	8.06E-04	
20	8.11E-04	9.08E-04	1.94E-04	1.01E-03	
21	1.02E-03	1.14E-03	2.46E-04	1.27E-03	
22	1.27E-03	1.43E-03	3.10E-04	1.58E-03	
23	1.59E-03	1.79E-03	3.93E-04	1.98E-03	
24	2.00E-03	2.25E-03	5.02E-04	2.50E-03	
25	2.50E-03	2.82E-03	6.29E-04	3.13E-03	
26	3.14E-03	3.53E-03	7.92E-04	3.93E-03	
27	3.94E-03	4.44E-03	9.97E-04	4.94E-03	
28	4.94E-03	5.57E-03	1.26E-03	6.20E-03	
29	6.21E-03	7.00E-03	1.59E-03	7.80E-03	
30	7.80E-03	8.80E-03	2.00E-03	9.80E-03	

The given time windows are adjusted due to the calibration time value (-1.0 µs).

Note: The gates numbered 1 to 7 are not used in the present survey.

Appendix 2: Calibration

On the 15th of october 2007 the wave form was measured for the following repetition frequencies 25 Hz. The plots below show the up and down ramp, respectively.

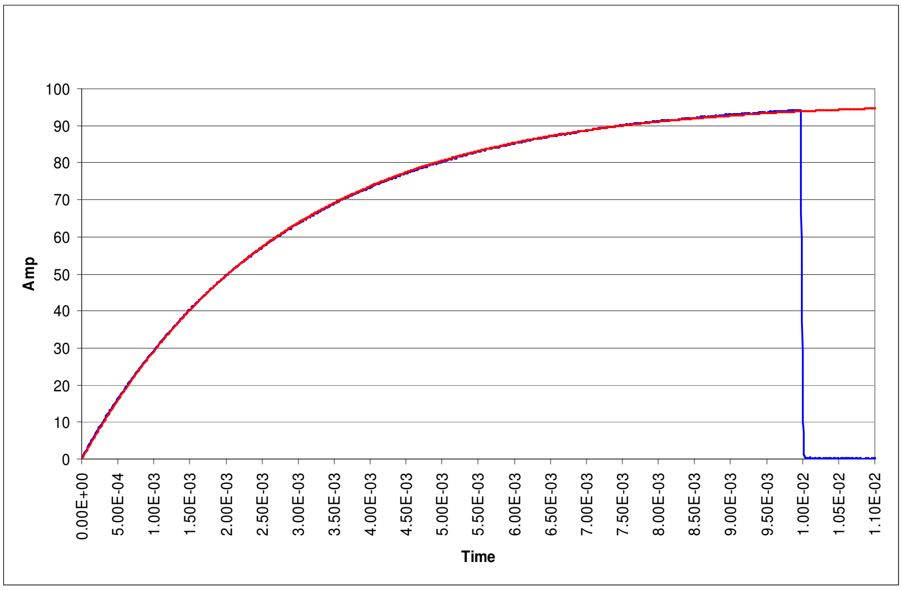


Figure 13 Ramp up at 25 Hz. Blue curve is the measured wave form. Red curve is the exponential function that fits the data. The current is 96.5 A and the decay constant τ = 360 s^{-1}.

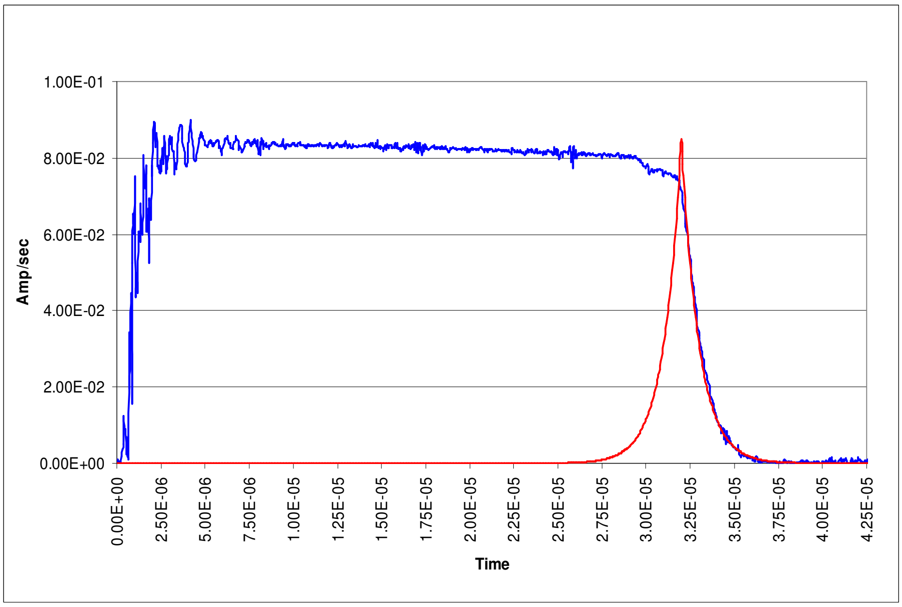


Figure *14 Ramp down at* 25 Hz. *Blue curve is the measured wave form. Red curve is the exponential function that fits the data. Avalanche mode* 32.0 µs. *Exponential mode* 32.0 µs to 40.0 µs. *Decay constant* 1.0 E6 s^{-1}. *The spikes are due to background noise, and noise in the oscilloscope while using a pickup coil for measuring the turn off.*

	Parameter	Value
Ramp up	Repetition frequency	25 Hz
	Decay constant, τ	360 s^{-1}
Ramp Down	Avalanche mode	32.0 µs
	Linear ramp dI/dt	3.13 E+06 A/s
	End avalanche mode	32.0 µs
	Decay const exp mode, τ	1.0 E6 s^{-1}

The complete SkyTEM equipment has been calibrated at the National Danish Reference Site on the the 29th of June 2006. The following plots show the measured data as well as the expected response in altitudes from 0 to 30 m.

The reference data are shown as blue curves and the measured data as red curves.

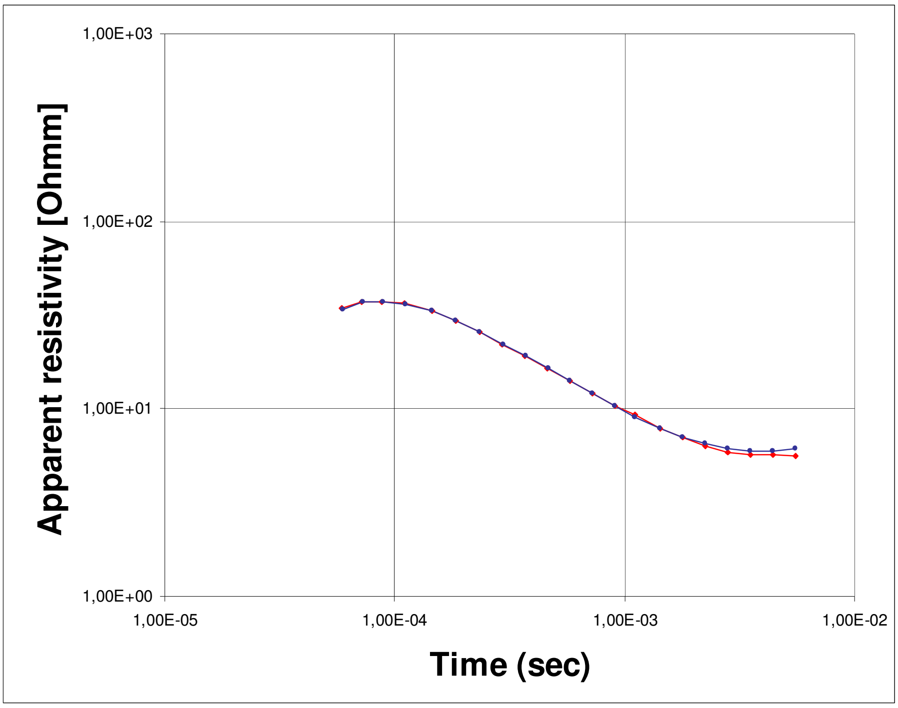


Figure 15. the 29th of June 2006. The frame is in 5 m altitude. Blue curve is the expected response, and the red curves are the actual measurements.

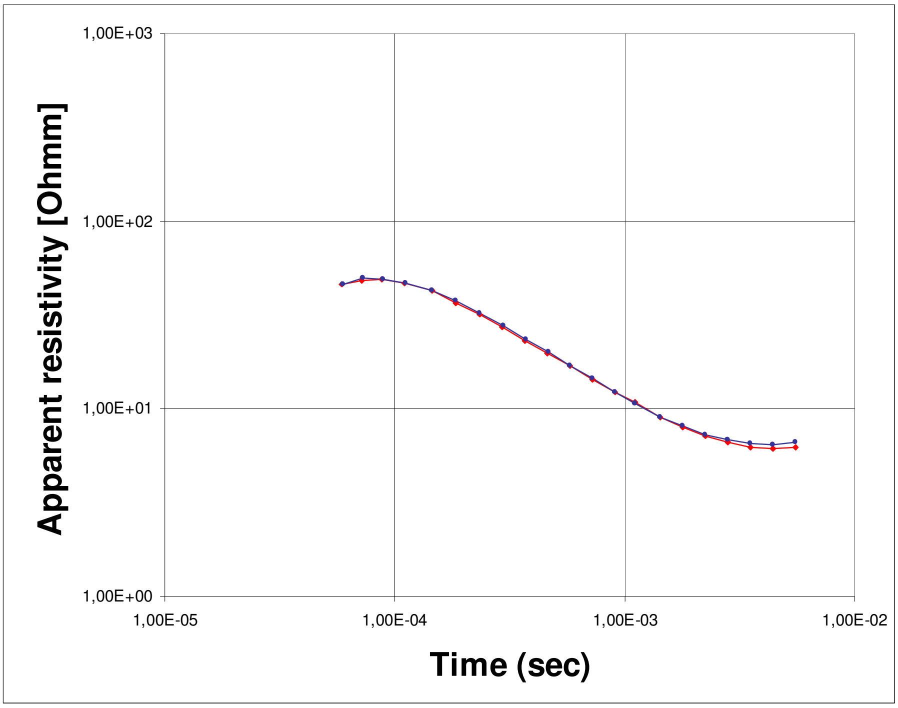


Figure 16. the 29th of June 2006. The frame is in 12.5 m altitude. Blue curve is the expected response, and the curves are the actual measurements.

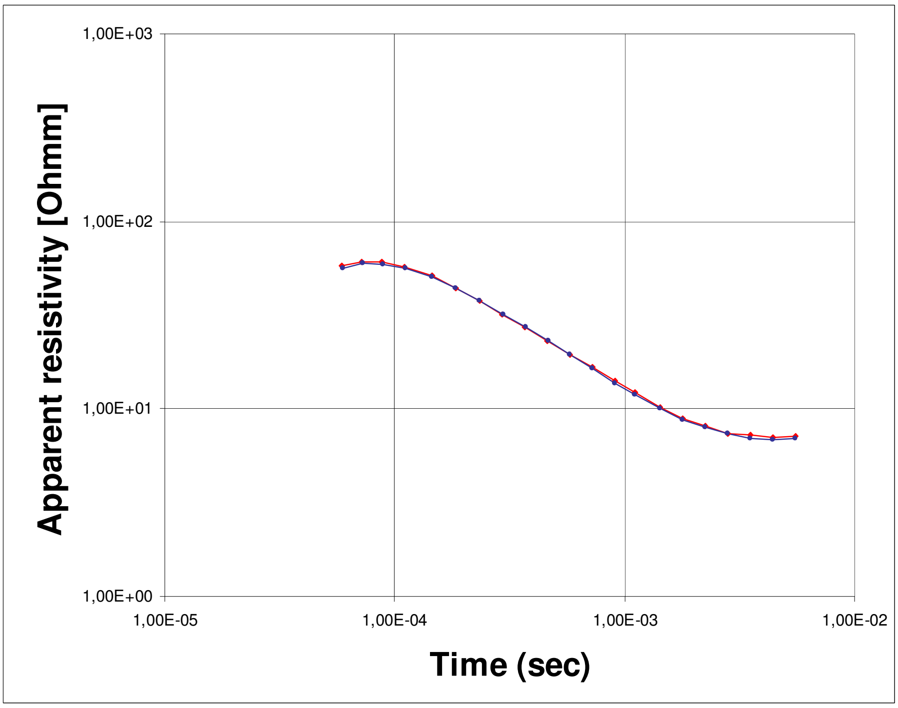


Figure 17. the 29th of June 2006. The frame is in 18 m altitude. Blue curve is the expected response, and the red curves are the actual measurements.

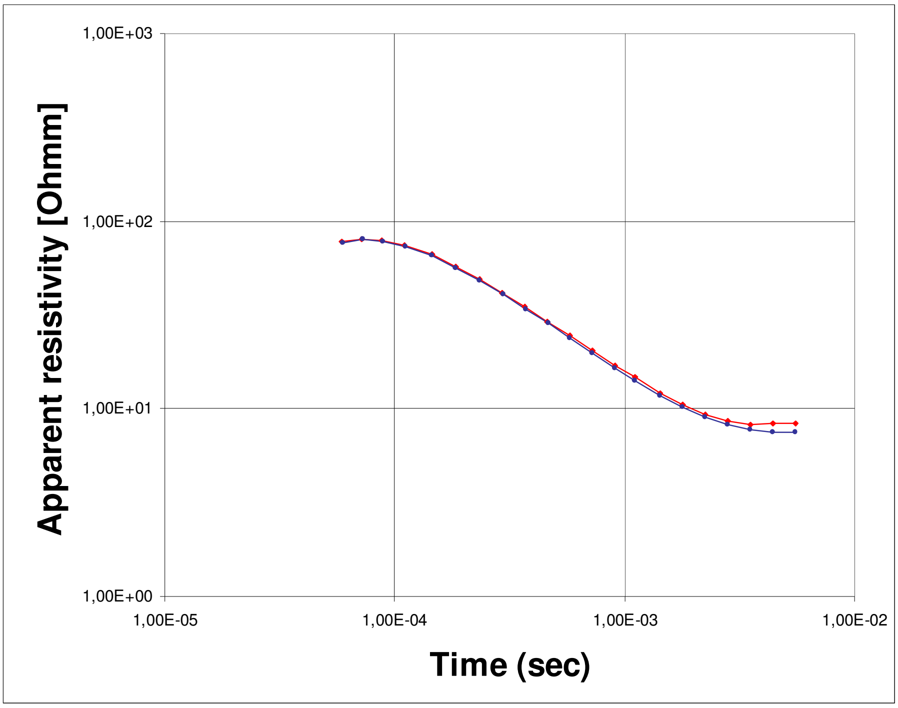


Figure 18 the 29th of June 2006. The frame is in 27 m altitude. Blue curve is the expected response and the red curves are the actual measurements.

Appendix 3: Line numbers

The line numbers are listed below together with information about the position and time for begin and end of line. The list is sorted by date and time.

Line #	Date	Time	Easting, Northing
100101	2007/09/07	06:42:09.059	475336.84,7364248.18
100101	2007/09/07	06:43:00.059	475826.87,7364713.42
100111	2007/09/07	06:44:05.059	475952.26,7364706.55
100111	2007/09/07	06:44:55.059	475461.41,7364206.84
100121	2007/09/07	06:45:40.059	475557.21,7364111.47
100121	2007/09/07	06:46:37.059	476253.08,7364830.38
100131	2007/09/07	06:47:23.059	476424.19,7364864.26
100131	2007/09/07	06:48:42.059	475600.47,7363977.99
100141	2007/09/07	06:49:12.059	475721.23,7363903.48
100141	2007/09/07	06:50:41.059	476703.25,7364927.25
100151	2007/09/07	06:51:14.059	477013.85,7365035.92
100151	2007/09/07	06:53:22.059	475788.02,7363833.22
100161	2007/09/07	06:55:36.059	475850.87,7363762.79
100161	2007/09/07	06:57:40.059	477194.01,7365075.47
100171	2007/09/07	06:58:17.059	477418.44,7365122.25
100171	2007/09/07	07:00:51.059	475978.45,7363662.48
100181	2007/09/07	07:01:22.059	476076.53,7363614.04
100181	2007/09/07	07:03:48.059	477663.24,7365168.21
100191	2007/09/07	07:04:05.059	477866.91,7365240.28
100191	2007/09/07	07:07:09.059	476195.79,7363522.84
100201	2007/09/07	07:07:33.059	476297.12,7363455.65
100201	2007/09/07	07:09:59.059	477982.86,7365138.25
100211	2007/09/07	07:10:21.059	478067.75,7365005.15
100211	2007/09/07	07:13:11.059	476402.23,7363342.39
100221	2007/09/07	07:15:29.059	476493.1,7363294.92
100221	2007/09/07	07:17:55.059	478115.74,7364904.89
100231	2007/09/07	07:18:09.059	478210.11,7364810.29
100231	2007/09/07	07:20:52.059	476576.38,7363194.34
100241	2007/09/07	07:23:14.059	476676.36,7363176.45
100241	2007/09/07	07:25:41.059	478271.5,7364707.61
100251	2007/09/07	07:25:55.059	478351.29,7364633.63
100251	2007/09/07	07:28:49.059	476807.45,7363068.01
100261	2007/09/07	07:29:29.059	476892.12,7362971.67
100261	2007/09/07	07:31:36.059	478437.85,7364526.06
100271	2007/09/07	07:32:06.059	478541.62,7364425.71
100271	2007/09/07	07:34:38.059	477008.29,7362893.01
100281	2007/09/07	07:35:17.059	477096.34,7362810.58
100281	2007/09/07	07:37:22.059	478582.8,7364347.93

100291	2007/09/07	07:37:52.059	478683.28,7364230.67
100291	2007/09/07	07:40:12.059	477174.08,7362716.19
100301	2007/09/07	07:40:43.059	477310.12,7362618.77
100301	2007/09/07	07:42:44.059	478734.3,7364147.12
100311	2007/09/07	07:43:18.059	478831.03,7364022.31
100311	2007/09/07	07:45:21.059	477357.6,7362573.47
100321	2007/09/07	07:45:55.059	477445.6,7362453.92
100321	2007/09/07	07:47:47.059	478885.81,7363933.73
100331	2007/09/07	07:48:11.059	478974.45,7363799.52
100331	2007/09/07	07:50:15.059	477504.84,7362348.11
100341	2007/09/07	07:50:42.059	477653.72,7362245.25
100341	2007/09/07	07:52:30.059	479041.05,7363736.7
100351	2007/09/07	07:53:04.059	479129.53,7363622.12
100351	2007/09/07	07:55:01.059	477724,7362205.33
100361	2007/09/07	09:09:48.059	479167.48,7363514.38
100361	2007/09/07	09:11:46.059	477809.91,7362144.91
100371	2007/09/07	09:07:36.059	477886.23,7362059.13
100371	2007/09/07	09:09:24.059	479256.37,7363400.79
100381	2007/09/07	09:05:06.059	479344.77,7363295.91
100381	2007/09/07	09:07:11.059	477992.03,7361950.85
100391	2007/09/07	09:02:59.059	478096.69,7361885.03
100391	2007/09/07	09:04:37.059	479408.19,7363204.26
100401	2007/09/07	09:00:25.059	479408.02,7363025.01
100401	2007/09/07	09:02:24.059	478208.91,7361812.03
100411	2007/09/07	08:58:50.059	478310.02,7361743.25
100411	2007/09/07	09:00:15.059	479448.12,7362909.57
100421	2007/09/07	08:56:01.059	479618.42,7362893.82
100421	2007/09/07	08:58:03.059	478378.64,7361629.01
100431	2007/09/07	08:54:20.059	478526.91,7361655.3
100431	2007/09/07	08:55:50.059	479669.29,7362771.29
100432	2007/09/07	08:52:23.059	478483.62,7361590.75
100432	2007/09/07	08:52:35.059	478603.16,7361730.96
100441	2007/09/07	08:49:05.059	479766.83,7362689.43
100441	2007/09/07	08:51:16.059	478567.79,7361491.12
100451	2007/09/07	08:47:21.059	478662,7361411.48
100451	2007/09/07	08:48:46.059	479843.71,7362613.29
100461	2007/09/07	08:45:07.059	479927.59,7362515.93
100461	2007/09/07	08:47:02.059	478782,7361334.65
100471	2007/09/07	08:43:24.059	478874.41,7361276.43
100471	2007/09/07	08:44:46.059	479997.1,7362413.43
100481	2007/09/07	08:40:36.059	480088.25,7362298.98
100481	2007/09/07	08:42:45.059	478970.29,7361179.06
100491	2007/09/07	08:39:08.059	479053.39,7361087.47
100491	2007/09/07	08:40:25.059	480153.36,7362198.41
100501	2007/09/07	08:35:49.059	480269.55,7362145.53

100501	2007/09/07	08:37:50.059	479187.94,7361051.47
100511	2007/09/07	08:34:22.059	479231.62,7360951.94
100511	2007/09/07	08:35:36.059	480343.16,7362026.63
100521	2007/09/07	08:04:23.059	479309.73,7360861.4
100521	2007/09/07	08:05:51.059	480426.6,7361962.05
100531	2007/09/07	08:06:14.059	480503.48,7361809.14
100531	2007/09/07	08:07:54.059	479449.03,7360750.8
100541	2007/09/07	08:08:09.059	479540.57,7360653.48
100541	2007/09/07	08:09:29.059	480578.84,7361739.61
100551	2007/09/07	08:09:53.059	480658.11,7361600.73
100551	2007/09/07	08:11:40.059	479625.15,7360588.76
100561	2007/09/07	08:12:09.059	479681.04,7360511
100561	2007/09/07	08:13:27.059	480691.43,7361503.97
100571	2007/09/07	08:14:04.059	480781.91,7361387.86
100571	2007/09/07	08:15:43.059	479828.69,7360430.12
100581	2007/09/07	08:16:01.059	479921.6,7360354.2
100581	2007/09/07	08:17:17.059	480853.31,7361317.26
100591	2007/09/07	08:17:51.059	480927.87,7361179.07
100591	2007/09/07	08:19:33.059	480033.78,7360280.61
100601	2007/09/07	08:20:08.059	480109.17,7360203.6
100601	2007/09/07	08:21:10.059	480997.49,7361098.12
100611	2007/09/07	08:21:45.059	481092.06,7360933.72
100611	2007/09/07	08:23:19.059	480200.71,7360095.05
100621	2007/09/07	08:23:35.059	480280.13,7359960.5
100621	2007/09/07	08:24:45.059	481133.13,7360847.62
100631	2007/09/07	08:25:29.059	481048.89,7360562.93
100631	2007/09/07	08:26:33.059	480360.14,7359902.19
100641	2007/09/07	08:26:48.059	480465.35,7359825.1
100641	2007/09/07	08:27:36.059	481042.15,7360439.57
100651	2007/09/07	08:28:15.059	481082.76,7360233.2
100651	2007/09/07	08:29:05.059	480563.49,7359741.38
100661	2007/09/07	08:29:22.059	480667.5,7359620.15
100661	2007/09/07	08:30:03.059	481057.41,7360089.35
100671	2007/09/07	08:30:40.059	481061.76,7359872.84
100671	2007/09/07	08:31:11.059	480758.31,7359567.8
100681	2007/09/07	08:31:28.059	480883.58,7359488.36
100681	2007/09/07	08:31:52.059	481097.68,7359771.27
200101	2007/09/07	09:14:55.059	481151.9,7360559.9
200101	2007/09/07	09:20:53.059	476734.34,7364922.19
200111	2007/09/07	07:58:14.059	475554.67,7364672.53
200111	2007/09/07	08:03:31.059	479742.93,7360549.45

Appendix 4: Control parameters

The following plots show the speed, altitude and the angle of the frame for every flight. Variations in the current, voltage on the transmitter and transmitter temperature are also shown.

The green line, depicting processed frame height, shows the input from HE1 and HE2 after the frame has been corrected from deviations, away from the horizontal plane and any obstacles on the ground e.g. trees. The processed frame height is the one used in the inversion routine.

Note the time scaling at the x-axis differs between the plots.

Turns at the end of flight lines and transport are shown as gaps in the bottom of the display

Appendix 5: Modeling and Inversion of the TEM Data

In this section, the particulars of modeling and inversion of TEM data will be described.

The model

The model used for inversion of the TEM data is a multi-layer model (MLM) with 30 layers. The layer thicknesses increase downwards as a hyperbolic sine. I.e. the depth to the layer boundaries increases linearly for small depths, thus the top layers are all of approximately the same thickness, and the depth to the layer boundaries increases exponentially with depth for large depths, so that the thickness of a layer is a factor times the previous one. The top layer is 10 m thick, and the asymptotic exponential factor is 1.25, corresponding to 10 layers per decade. The layer thicknesses and layer boundary depths are seen in the table below. The vertical smoothness constraint on the MLM imposing identity between neighboring layers has a relative uncertainty of 0.5.

Inversion - The initial model

The initial model for all inversions is the previously mentioned 30-layer MLM with a resistivity of 200 Ωm in all layers, i.e. the initial model is essentially a homogeneous half space. Throughout, we have used the L_1-norm in the optimization to produce as blocky models as possible.

Data and noise model

The inaccuracy of TEM data is caused by ambient noise. This noise is reduced by stacking delay time series, and by applying appropriate filters in the receiver system.

For TEM data recorded at middle latitudes on the northern hemisphere, experience shows that the noise consists of two types of contributions: one source comes from single frequency radio transmitters, and the other is an ambient wideband noise. The width of the time gates of the SkyTEM system increase approximately exponentially with delay time which helps reduce the effective noise. The single frequency noise is dominated by transmitters with frequencies above 10 kHz, and as such dominating at delay times earlier than 100 *μ*s. The effect of exponential gating is to make this noise decrease with time, t, as $1/t$. For the wideband noise, the exponential gating makes the effective noise decrease as $1/\sqrt{t}$, and this noise dominates at times later than 100 *μ*s. Our noise model is expressed as a sum of the two contributions, and it can be characterized by two parameters: the time, t_0, when the two contributions are of equal size and the amplitude at that time, $V_0 = V(t_0)$.

The noise is assumed to be partly a $1/t$ noise from radio transmitters, and partly

$1/\sqrt{t}$ noise from log gated ambient sources. The two contributions are assumed to be independent, so we have:

$$V = \sqrt{\left(\frac{a}{t}\right)^2 + \left(\frac{b}{\sqrt{t}}\right)^2} \qquad (1)$$

If we assume the two terms to be of equal (squared) weight at the transition point t_0, we find

$$\left(\frac{a}{t}\right)^2 = \left(\frac{b}{\sqrt{t_0}}\right)^2 \Rightarrow \left(\frac{b}{a}\right)^2 = \left(\frac{\sqrt{t_0}}{t_0}\right)^2 = \frac{1}{t_0} \Rightarrow b = \frac{a}{\sqrt{t_0}} \qquad (2)$$

With these assumptions, the noise function is uniquely given by its value at the transition point, V_0.

$$V = \sqrt{\left(\frac{a}{t}\right)^2 + \left(\frac{b}{\sqrt{t}}\right)^2} = \frac{a}{t}\sqrt{1 + \left(\frac{a}{\sqrt{t_0}\sqrt{t}} \cdot \frac{t}{a}\right)^2}$$

$$V = \frac{a}{t}\sqrt{1 + \frac{t}{t_0}} = V_0 \quad for \quad t = t_0 \Rightarrow a = \frac{V_0 t_0}{\sqrt{2}} \Rightarrow \qquad (3)$$

$$V = \frac{V_0}{\sqrt{2}} \frac{t_0}{t} \sqrt{1 + \frac{t}{t_0}}$$

The parameters V_0 and t_0 can be pragmatically determined for a given data set.

Data insufficiency

For SkyTEM data, the insufficiency lies primarily in the limited delay time range that can be obtained. The earliest obtainable time gate is determined by the turn-off of the Tx current, and the latest useful time gate is determined by the signal to noise ratio. Increasing the Tx moment will give better measurements at late times, and thus improve the depth penetration, but an increased Tx moment will increase the turn-off time and thus remove early-time gates, thereby making the near-surface resolution poorer. This trade-off is often solved by alternating transmitting a low moment that can be turned off quickly to give good near-surface resolution, and a high moment that will improve the signal-to-noise ratio at late times, thus improving depth penetration.

Appendix 6: Model sections and conductivity and resistivity intervals

Model sections, conductivity and resistivity interval maps for Mo i Rana, Area4 - Norway can be found in digital form as pdf files.

Model Sections

The top plot in the model sections shows the inverted models with topography where the conductivity and resistivity of the individual layers are color coded according to the color bar. The actual flight elevation is shown with a black dotted line above the model section.

The flight lines have been superimposed to straight lines running from begin to end of a flight line. The profile coordinate gives the distance along the line in meters.

The conductive features of the model sections are emphasized by using color coding that shows conductivity on a linear scale. The resistivity (the inverse of conductivity) is shown on a logarithmic scale, thus conductive and resistive feature appear with the same weight.

Below the model section is a plot of the relative uncertainty of the model. Red indicates where data has contributed perceptibly to the determination of the conductivity. Blue indicate where conductivity or resistivity is more determined by the smoothness constraint (i.e. the vertical constraint) than the data

Below the plot of relative uncertainties is a plot of the residuals of the inversions: blue indicates the data residual and green the total residual.

The gate plot at the bottom shows the forward response compared to the actual values of chosen gate numbers.

Average conductivity and resistivity intervals

For the complete survey area - or parts thereof - so-called interval conductivity/ resistivity maps are produced by contouring the average conductivity and resistivity in a certain depth or elevation interval.

Appendix 7: Digital data

The digital data are:

└ *Report*

The report and appendices (PDF-format)

└ *Line File*

Ascii line file (line number, time, coordinate (Latitude/longitude, WGS84))

└ *XYZ TEM data file*

XYZ ascii files containing the “raw” TEM data

└ *XYZ TEM Model result*

XYZ ascii files containing the TEM model result

└ *XYZ Magnetometer data*

XYZ ascii files containing the magnetometer data

└ *MapInfo TAB files*

- └ Planned flight lines
- └ Interval conductivity and resistivity maps
- └ Contoured magnetometer data
- └ Contoured DTM
- └ Contoured Raw Channel plots of selected channels