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Forsmark site investigation

Inversion of helicopter-borne electromagnetic measurements

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May 2005

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Abstract

This report describes the execution and the results of inversion of helicopter borne electromagnetic data from Forsmark. The data have been calibrated and levelled with the help of ground geophysics, borehole information, soil mapping and known seawater depths.

The calibrated and levelled data were inverted to a model consisting of two horizontal layers where the upper layer corresponds to the soil cover (land areas) or sea water (sea areas) and the lower layer corresponds to the bedrock (land areas) or combined soil and bedrock (sea areas). The results of a large number of inversions at grid nodes were stitched together to form a continuous description of the layer parameters. The inversion was constrained by the same type of information as was used for calibration and levelling.

The output of the inversion was grids of soil cover resistivity and thickness and bedrock resistivity for land areas. The output for sea areas was a grid of water depths. The results were good although the land results need to be verified by other information. Low bedrock resistivity was indicated for ultramafic rocks east of Johannisfors and for an area south of the Forsmark nuclear power plant. Several lineaments could be seen in the seafloor topography and those results have been used in the integrated lineament interpretation of the Forsmark area.

Sammanfattning

Denna rapport beskriver utförandet och resultat från inversion av helikopterburna elektromagnetiska mätdata från Forsmark. Data har kalibrerats och nivellerats med hjälp av markgeofysik, borrhålsinformation, jordartskartering och kända vattendjup.

Kalibrerade och nivellerade data inverterades till en modell bestående av två horisontella lager där det övre lagret motsvarar jordtäcket (landområden) eller havsvatten (havsområden) och det undre lagret motsvarar berggrunden (landområden) eller jord och berg i kombination (havsområden). Inversionen styrdes av samma typ av information som användes vid kalibrering och nivellering.

Resultatet av inversionen var rasterfiler av jordtäckets tjocklek och resistivitet och berggrundens resistivitet för landområden. För havsområden utgjordes resultatet av en rasterfil med vattendjup. Resultaten var goda men landresultaten behöver verifieras med andra metoder. Låg berggrundsresistivitet indikerades för ett område med ultramafiska bergarter öster om Johannisfors och ett område söder om Forsmarks kärnkraftverk. Åtskilliga lineament kunde noteras i havsbottentopografin vilket har nyttjats vid den integrerade lineamentstolkningen för Forsmarksområdet.

Contents

1 Introduction

SKB performs site investigations for localization of a deep repository for high level radioactive waste. The site investigations are performed at two sites, Forsmark and Simpevarp.

This document reports the results gained from inversion of helicopter borne electromagnetic measurements in the Forsmark area. The work has been performed in accordance with AP PF 400-03-092 (SKB internal controlling document), see Table 1-1.

Inversion is a process where measurement data are transformed into a model of physical parameters that describes the subsurface. In the present work a model consisting of two horizontal layers has been used. Over land areas the upper layer corresponds to the soil cover whereas the lower layer corresponds to the bedrock. In sea areas, the upper layer corresponds to the water and the lower layer corresponds to soil and rock in combination. The model is a great simplification of the real conditions. In reality, the soil consists of several soil types that might be layered on top of each other. The resistiviy has lateral variations and the layer interfaces are not planar and horizontal. The simple model is however used since it will, in most cases, be a valid simplification and also because the resolution of the measurements is not high enough to resolve the complex geology more in detail.

Table 1-1. Controlling document for the performance of the activity (SKB internal controlling document).

Activity plan	Number	Version
Inversion av elektromagnetiska mätningar från helikopter	AP PF 400-03-092	1.0

2 Objective and scope

The purpose of this work is to transform the electromagnetic data into a model that describes the soil and the bedrock properties of the Forsmark area. The raw data can be visualized e.g. in the form of apparent resistivity for different frequencies but it is very difficult for an interpreter to know if the source of an anomaly is within the bedrock or in the soil cover. The inversion might point out areas of anomalously low bedrock resistivity or large soil depths. The inversion is also performed over sea areas and the result is bathymetric data. Bathymetric measurements have been performed by traditional sonar techniques in the Forsmark area but there are some gaps in the data e.g. in some near-shore areas that were inaccessible for the ship borne survey. These gaps can be filled by bathymetric information from the inversion.

3 Execution

3.1 Survey parameters

Electromagnetic measurements from helicopter have been performed in the Forsmark area by the Geological Survey of Norway with a Geotech Hummingbird system /1/. The instrumentation consists of transmitting and receiving coils mounted in a bird that is towed 30 m below the helicopter. The nominal flight height was 60 m above ground resulting in a height of the bird of 30 m above ground. The helicopter pilot was however, due to safety considerations, at occasions forced to ascend to higher altitudes to avoid power lines, high trees etc.

The instrumentation takes measurements at five frequencies according to Table 3-1.

Table 3-1. Measurement frequencies of the Geotech Hummingbird system.

Frequency #	Frequency (Hz)	Coil-orientation	Coil-separation (m)
1	7,001	Vertical co-axial	6.0
2	6,606	Horizontal co-planar	6.0
3	980	Vertical co-axial	6.0
4	880	Horizontal co-planar	6.0
5	34,133	Horizontal co-planar	4.2

The surveyed area can be seen in Figure 3-1. A larger area was covered with north-south lines with 50 m separation and with east-west tie-lines with 500 m separation. Additionally, a central area was covered with east-west lines with 50 m separation. In a separate survey, vertical electrical soundings (VES) were performed along the east-west tie-lines /2/.

The secondary EM field is measured in the presence of the much stronger primary field. This will have the effect that very small changes in transmitter-receiver geometry, coil sensitivity and several other factors will introduce errors in the measurements. The levelling of the system was checked by ascending the system to at least 300 m ground clearance and using the readings at those occasions as the "zero levels" of the system. The procedure was repeated with approximately 20 minutes intervals since e.g. temperature changes might introduce drift.

The gain of the system was set with the help of calibration coils while the system was on the ground and the phase was set by placing a ferrite rod close to the coils.

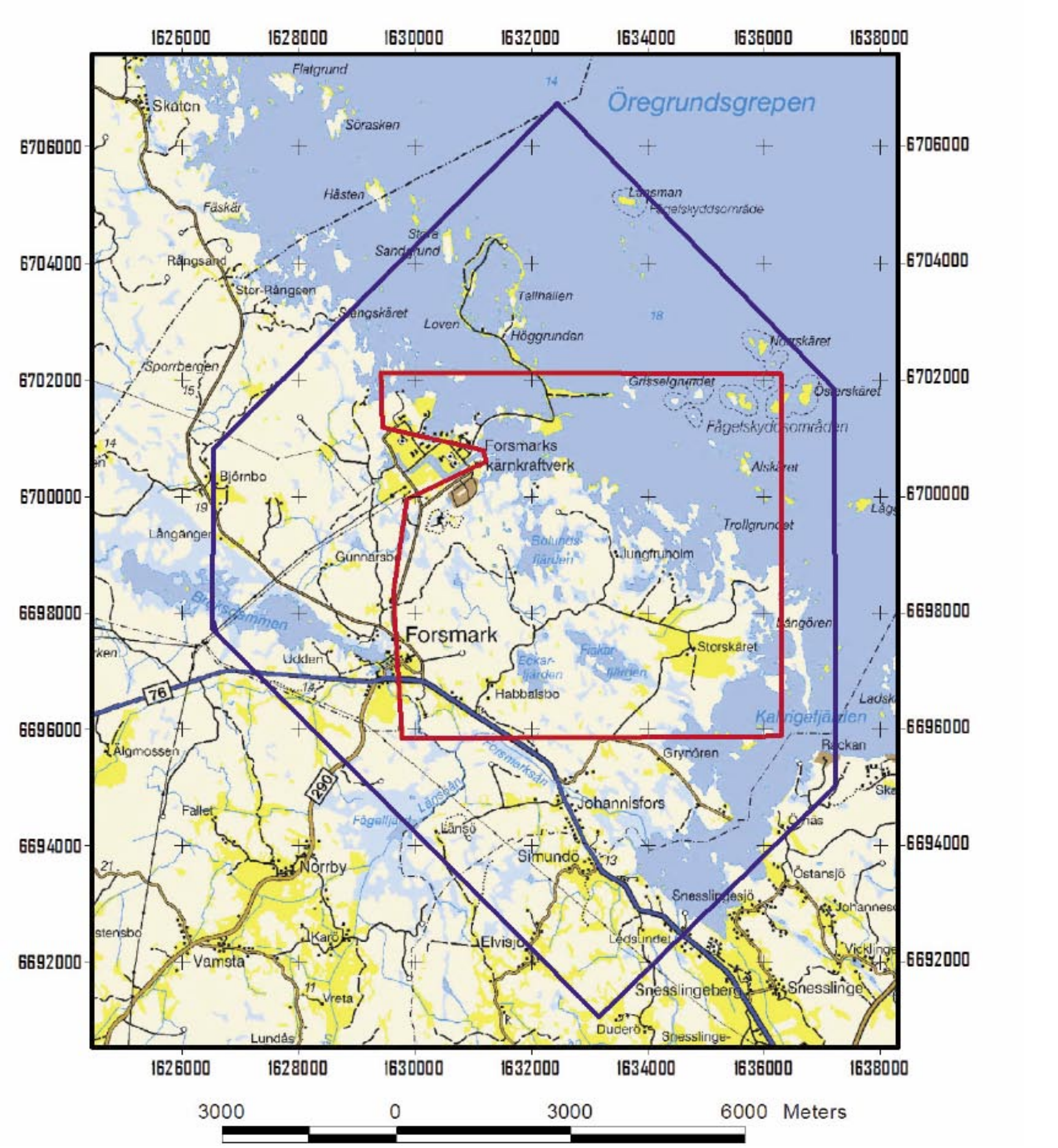

Figure 3-1. Coverage of the helicopter-borne geophysical survey at Forsmark. The blue line shows the area covered by north-south survey lines and the red line shows the area covered by east-west lines. Measurements could not be performed close to the Forsmark power plant.

3.2 Overview of inversion method

The procedures described above will, in most cases, be sufficient to obtain data that can be used in qualitative interpretations of the electrical properties of the ground. The survey at Forsmark was however conducted over highly resistive crystalline rock which means that the secondary fields will become very weak and the levelling procedure with ascents to ground-effect free altitude will not suffice. The aim of this project was also to make quantitative modelling of the data in the form of inversion. This means that correct gain and phase calibration is crucial for successful results. A special procedure has therefore been developed /3/.

The basic model for the inversion is a two-layer model where the upper layer corresponds to the soil cover and the lower layer corresponds to the bedrock (Figure 3-2). The conditions at Forsmark are such that the survey cannot resolve more than one layer within the soil cover. Two- or three-dimensionality of the ground is simply ignored during the inversion. This is of course a simplification compared to the actual geological conditions which should be kept in mind when the results are analyzed. Inversion is performed for a very large number of locations and the results are stitched together to form a continuous description of the soil cover and bedrock electrical properties of the area.

The Forsmark survey area is partly covered by sea water that is electrically well conducting. A corresponding inversion can be done for the sea areas. The upper layer will then correspond to the sea water that has a known electric resistivity. The lower layer is the sea-floor. The electrical properties of the sea-floor cannot be resolved.

Inversion is usually carried out by iteratively finding a model with such properties that the difference between the survey data and the synthetic response of the model to the measurements system is minimised in a least-squares sense /4, 5/. The inversion process will however not produce a unique solution. There are an infinite number of solutions that produces least-squares fits that are within the measurements errors. It is therefore

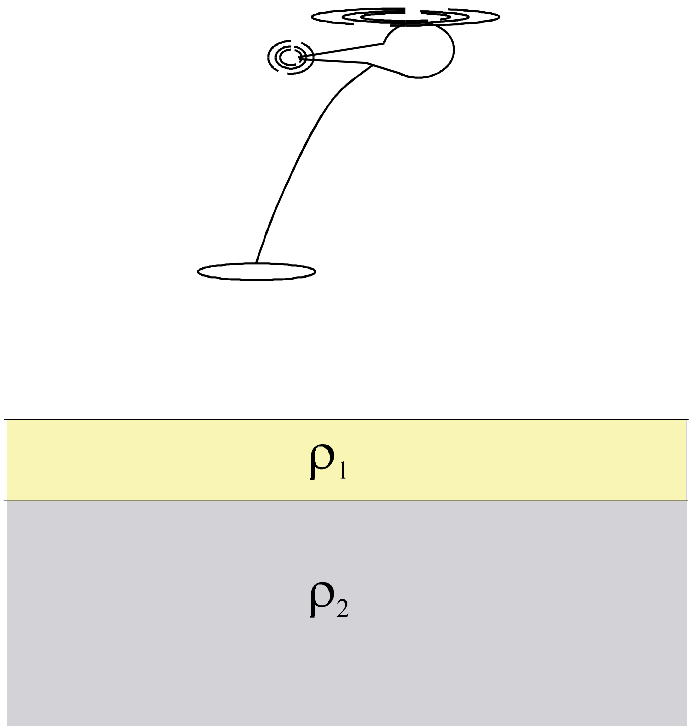

Figure 3-2. *Basic model for the inversion. The upper layer corresponds to the soil cover and the lower layer corresponds to the bedrock. The soil cover thickness and resistivity and the bedrock resistivity is the output of the inversion.*

common to put some constraints on the model so that the solution is compatible with e.g. known geology or expected physical properties. Such constraints can be implemented by adding extra "data" to the data vector in the form of values for the different model parameters /6, 7/. The data are weighted by normalizing them with their variance. This means that the output of the inversion is not forced to take the value of a constraint unless the variance of that constraint is very small.

In this work the constraints are of two types:

1. Known or estimated layer parameters from ground geophysics, drilling and soil mapping are used to produce maps of expected layer parameters through inverse distance weighting and other methods (see Section 3.6 below). The variances of the parameters are also estimated resulting in e.g. low variance for the soil cover thickness close to drilling locations. Known water depths are used in a similar way for sea areas.
2. Stations for Vertical Electrical Soundings (VES) are used as seed points for the inversion. Inversion starts at these locations and progresses at a gradually increasing distance. When a new solution is sought, the solutions for solved neighbouring points are used as constraints so that lateral similarity between points is achieved. The root-mean-square residual is used for weighting.

Careful calibration and levelling must be performed prior to inversion. This can be done by utilizing the locations where the electrical structure of the ground can be estimated, i.e. at the VES stations and where bathymetric data are available (sea water resistivity is known and the sea-floor resistivity is in practice infinite). The synthetic response of the VES models and the sea water to the airborne EM-system is calculated and compared to the survey results. The gain factors of the system are estimated for each measured component by linear regression analysis. Phase calibration can be done in a similar way. However, no significant phase errors appeared in the data.

The VES stations are placed along the tie-lines of the survey. The tie-line data can therefore be levelled, on a flight by flight basis, by comparing the data with synthetic responses of layered earth models interpreted from the VES measurements. An exact fit between the synthetic data and the survey data cannot be expected since the airborne survey and the VES measurements are e.g. unequally affected by 2D- or 3D-structures in the ground. However, a smooth trend can be subtracted from the data. The levelled tie-line data can then be used to level the ordinary survey lines by comparing the data at crossover points. The EM response of the ground is a function of flight height and a correction based on an inverse power formula was applied to the tie-line data. The difference in flight height between tie-lines and survey lines was in general moderate so this simple correction is not expected to introduce any serious errors. Crossover points at gradients in the EM response were ignored or judged less reliable when comparing tie-line data with survey line data.

The work flow of the inversion process is illustrated in a simplified manner in Figure 3-3.

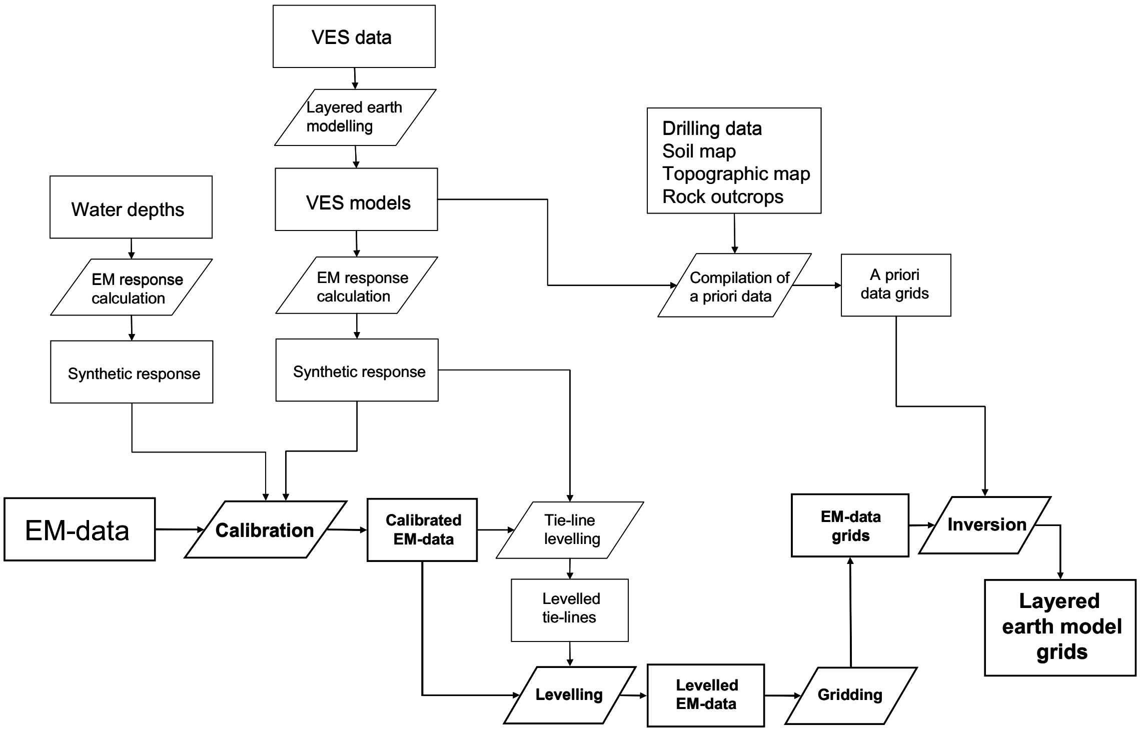

Figure 3-3. *Work flow of the inversion process for land areas. The input EM-data have undergone basic processing, including levelling with the help of high-altitude readings. The work flow for sea areas is identical with the exception of input data for a priori information.*

3.3 Pre-processing of EM-data

The basic processing of the survey data was performed by Peter Walker, Geophysical Algorithms as a part of the contractors (NGU) work /1/. However, the survey was affected in a serious way by cultural features like power lines and radio transmitters, resulting in noisy data and irregular and sudden level shifts for two of the frequencies. An extra effort was therefore done to reduce the effect of the noise /8/. The level shifts were correlated between the two affected frequencies and the shifts could therefore be removed after transformation of the data to the principal component domain. Filtering was also done with both linear and non-linear filters to reduce the effect of noise. Even though the noise was greatly reduced it should still be noted that the data quality was poorer than what would be expected for a survey in an area with less cultural noise.

3.4 Calibration of data

Vertical electrical soundings (VES) have been performed at 30 positions within the survey area (Figure 3-4) /2/. The synthetic response of the EM-system to the layered earth models of VES-stations was calculated with the flight height extracted from the altimeter data. Similarly, the EM response of the sea water at locations with known water depth /9/ was calculated. The resistivity of the brackish sea water is known to be 1.0 Ωm. The resistivity of the sea-floor is not resolved by the frequencies of this EM-system due to the low resistivity of the sea water. The sea-floor resistivity was set

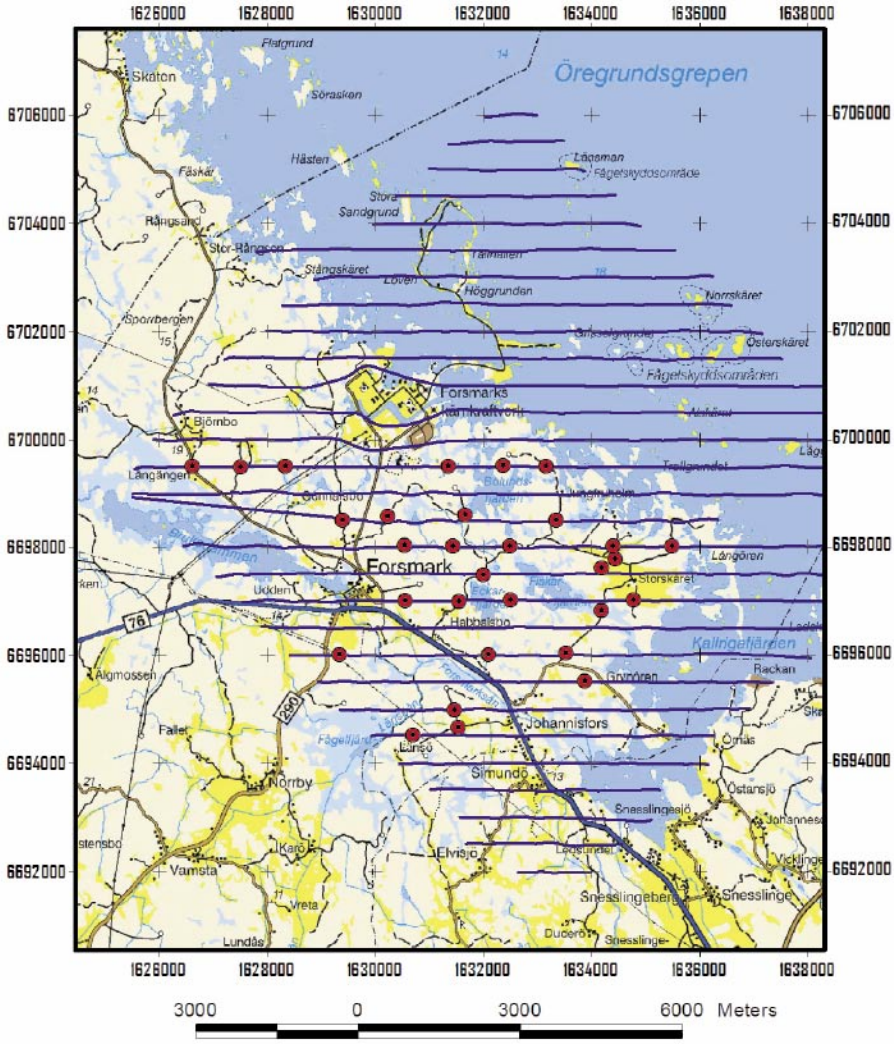

Figure 3-4. *Positions of electrical sounding stations (red symbols). The stations have been placed close to the 500 m separated east-west tie-lines of the helicopter-borne survey (solid blue lines). Six sounding stations can e.g. be found along the tie-line at nominal northing 6,699,500 m.*

to 500 Ω m in the calculations which is roughly the resistivity of rock samples from the area when soaked in salt water. The resistivity of the rock and soil is frequency dependent. However, measurements on rock samples have shown that the chargeability of all common rock types in the area is quite small /10/. The frequency dependence has therefore been ignored.

An example of the comparison between survey data and synthetic responses can be seen in Figure 3-5. The figure shows a linear relationship for this component (in-phase, 34 kHz) and similar linear relationships could be seen for all other components. The slope of the linear trends does not equal 1.0. Instead the values according to Table 3-2 were found. These values where then applied as gain correction factors to the data.

Highly magnetic rocks occur within the survey area that produce strong aeromagnetic anomalies /8, 10/. These rocks show up as negative anomalies for the in-phase components but no effect can be seen in the quadrature components. This implies that the phase calibration of the system is correct and no corrections needed.

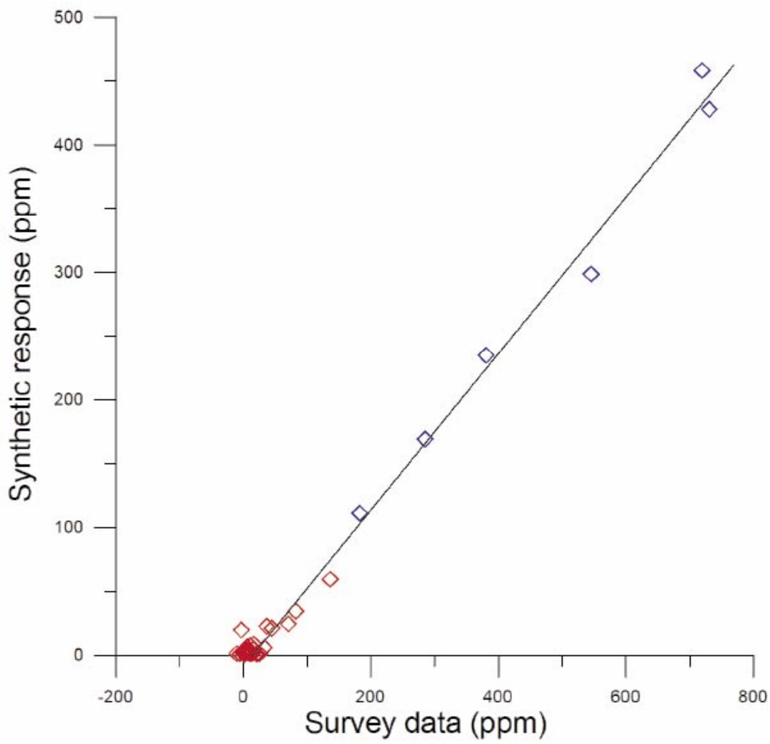

Figure 3-5. *Comparison between survey data (in-phase component, 34 KHz) and synthetic response for VES-models (red symbols) and sea water (blue symbols). The slope of the straight line corresponds to the gain correction factor for this component. The survey data have been levelled with the help of ground-effect free altitude readings.*

Table 3-2. Gain correction values for all EM-components.

Frequency #	Frequency (Hz)	In-phase component	Quadrature component
1	7,001	0.766	0.645
2	6,606	0.918	0.821
3	980	1.143	0.879
4	880	1.102	0.841
5	34,133	0.619	0.494

3.5 Levelling of data

3.5.1 Levelling using electrical soundings

With two exceptions, the VES stations in Figure 3-4 were placed close to the east-west tie-lines of the survey area. This means that most of the sounding locations were over-flown during the two flights when tie-line data were collected (flight 25 and 26).

The difference between the system response of the layered earth VES models and the gain corrected survey data as a function of record number for flight 25 can be seen in Figure 3-6. Even though the survey data have been levelled with the help of high-altitude readings some drift is evident in the graphs shown in Figure 3-6. The solid lines in the figure corresponds to second order polynomials that have been used to model the drift.

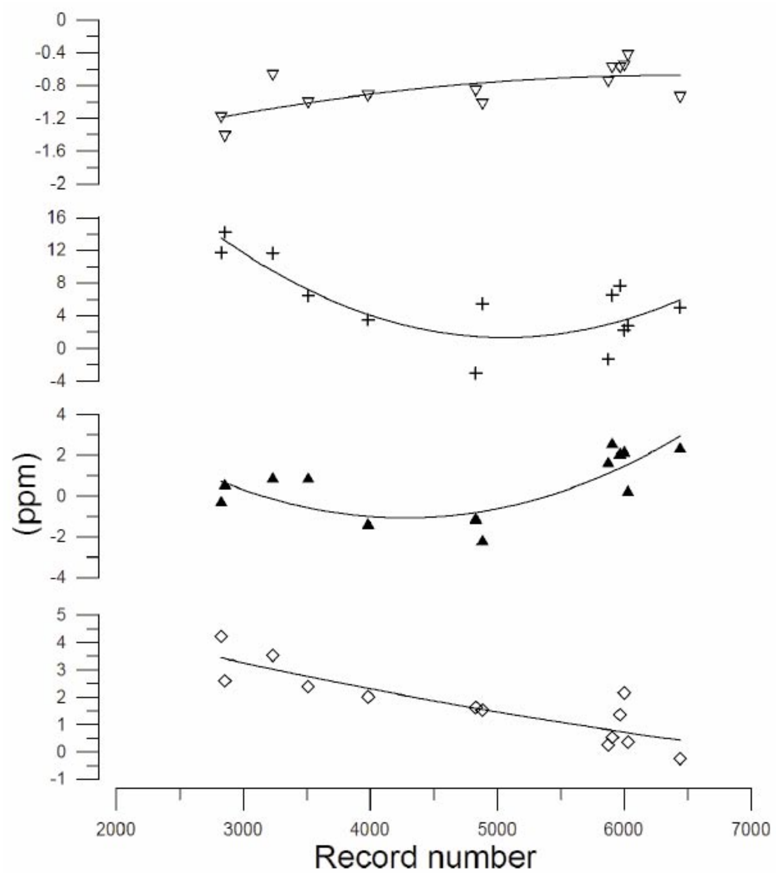

Figure 3-6. *Difference between synthetic responses to VES layered earth models and gain corrected survey data, flight 25. From top to bottom: 980 Hz quadrature, 34 kHz in-phase, 980 Hz in-phase and 7 kHz in-phase components. The full-drawn curves correspond to second-order polynomial fits to the differences. Note the difference in scale for the different components.*

Levelling of flight 25 and 26 has been performed by subtracting this drift. Two sounding stations which coincided with anomalies in the EM data were omitted and also two stations located on bogs smaller than the footprint of the EM system.

The data for frequency number 2 (6,606 Hz) were of poor quality for flight 25. No reflight was performed since data coverage was of higher priority during the time frame available for the survey. No levelled data for this frequency for flight 25 are therefore available.

3.5.2 Levelling using tie-lines

The north-south survey lines were levelled with the help of the levelled east-west tie-line data. Some of the lines had only a very small number of suitable crossovers with tie-lines and the work was therefore performed as a three-stage process.

1. A selected subset of north-south lines were levelled with the help of the tie-lines
2. The 50 m spaced east-west survey lines were levelled with the help of the north-south lines that was the output of 1. The northern part of the east-west survey was mainly over sea and was therefore not included.
3. All the north-south lines were levelled with the help of the tie-lines and the output of 2.

The EM response of the ground is a function of the height above ground of the measuring system. The tie-line data and survey line data at crossover points are therefore not directly comparable unless a correction for possible height differences is applied. This was done by modelling the height dependence corresponding to a resistivity structure with an inverse power function:

$S = A \cdot h^{-p}$

Where S is a measured secondary field component, A is a function of the resistivity structure of the ground, h is the height of the measuring system above ground and the exponent p is a constant to be determined. An example where the quadrature component of frequency 5 (34 kHz) has been calculated for three different two-layer models can be seen in Figure 3-7. The solid lines correspond to fits of inverse power functions to the calculated responses. The fit is very good in all cases, even though the value for p is different in the three cases (Table 3-3).

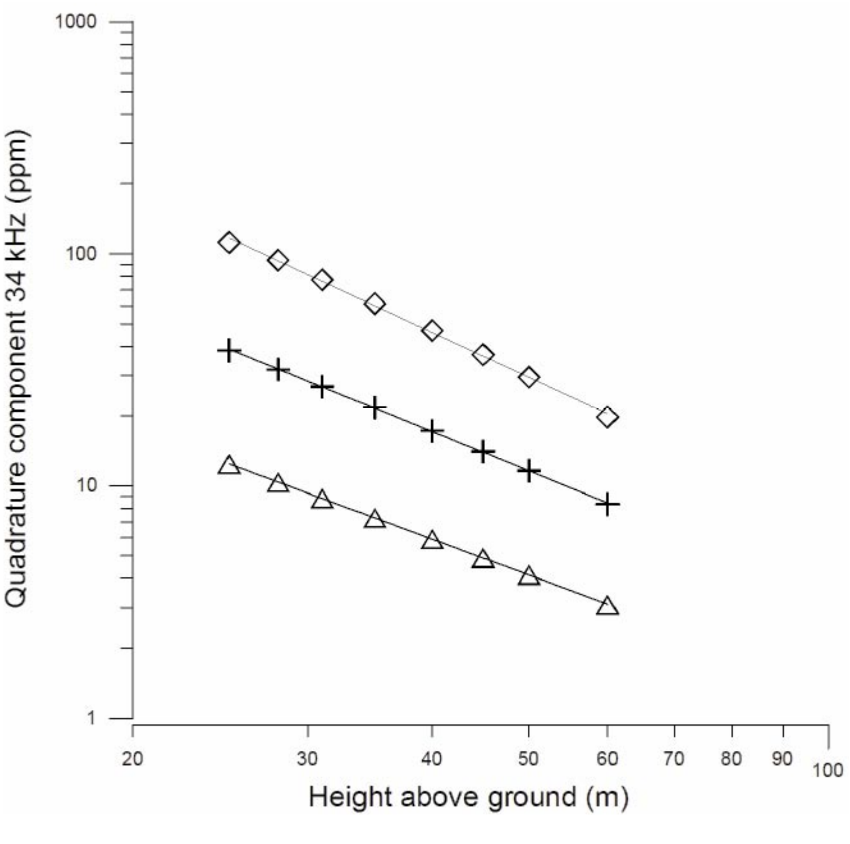

Figure 3-7. *Calculated quadrature component for frequency 5 (34 kHz) for three different layered earth models (symbols). The models parameters are given in Table 3-3. Model 1 is shown with diamonds, model 2 with crosses and model 3 with triangles. Fits of inverse power functions can be seen as solid lines.*

Table 3-3. Models for estimating height dependence of EM response (34 kHz, quadrature component).

Model #	Resistivity layer 1 (Ω m)	Thickness layer 1 (m)	Resistivity layer 1 (Ω m)	Exponent p
1	200	7.5	3,000	1.99
2	500	4	5,000	1.74
3	1,000	2	15,000	1.58

Tie-line crossovers in areas with fairly uniform high resistivity properties are preferred for levelling. A value of 1.6 for the exponent p was therefore selected for modelling the height dependence for this component. The errors introduced in areas of lower resistivity are however quite small since the height differences in general are within a few metres. The same calculations have been performed for all other measured components. The variations in p-values are however smaller for lower frequencies and even smaller for in-phase components.

An example of the levelling of a north-south line can be seen in Figure 3-8. The procedure was performed in an interactive manner line by line.

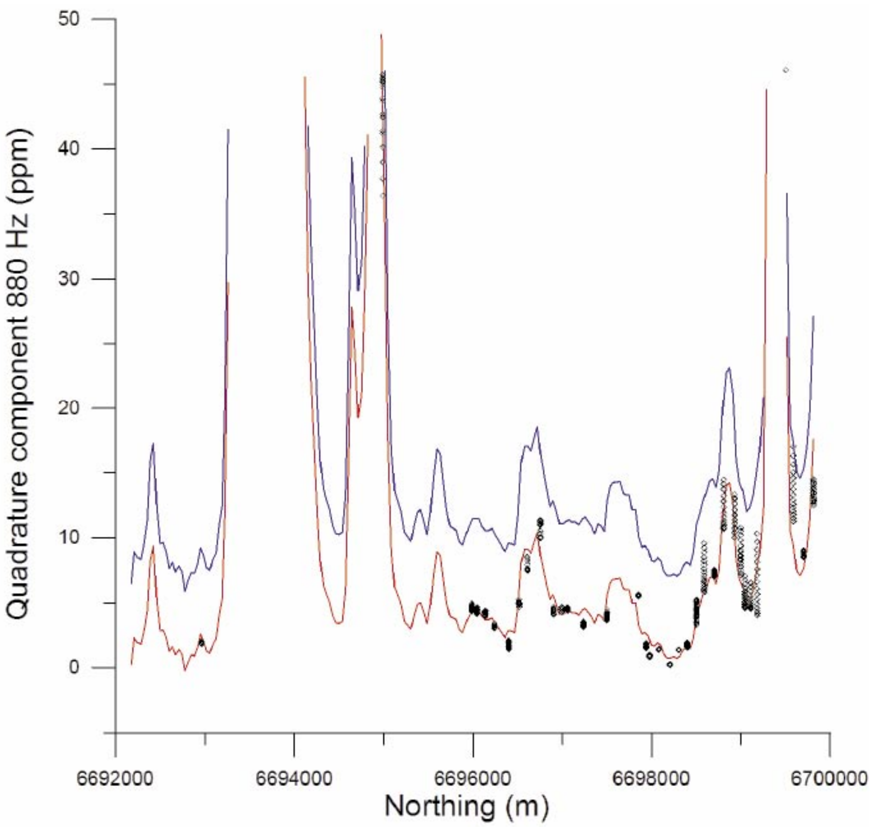

Figure 3-8. *Levelling of a north-south line at nominal easting 1,634,200 m. Quadrature component 880 Hz after basic processing (blue line), levelled east-west line data at crossovers (black symbols) and levelled data (red line). Gain correction according to Table 3-2 and a subtraction of 5.2 ppm was done in this case.*

Data from the perpendicular lines at a distance within 25 m of the crossovers are also shown in Figure 3-8. This makes it easy to identify crossovers at gradients in the tie-line data that are unsuitable for levelling.

Rocks with high magnetic susceptibilities will cause negative in-phase anomalies. The in-phase components of the two lowest frequencies were used to estimate the effect of magnetic rocks. These components are expected to show insignificant anomalies due to induced currents in the ground. Negative anomalies were set to zero and the magnitude of this correction was also applied to the higher frequency in-phase components after compensation for differences in coil-separation.

Apparent resistivity maps based on the levelled data for the quadrature components of frequency 1 (7,001 Hz, coaxial coils) and frequency 2 (6,606 Hz, coplanar coils) can be seen in Figure 3-9. The frequencies are very close although with different coil orientations. The apparent resistivity maps are very similar and with very little stripes due to the line orientation (except for some high-resistivity areas). This indicates that the levelling of these components has been successful.

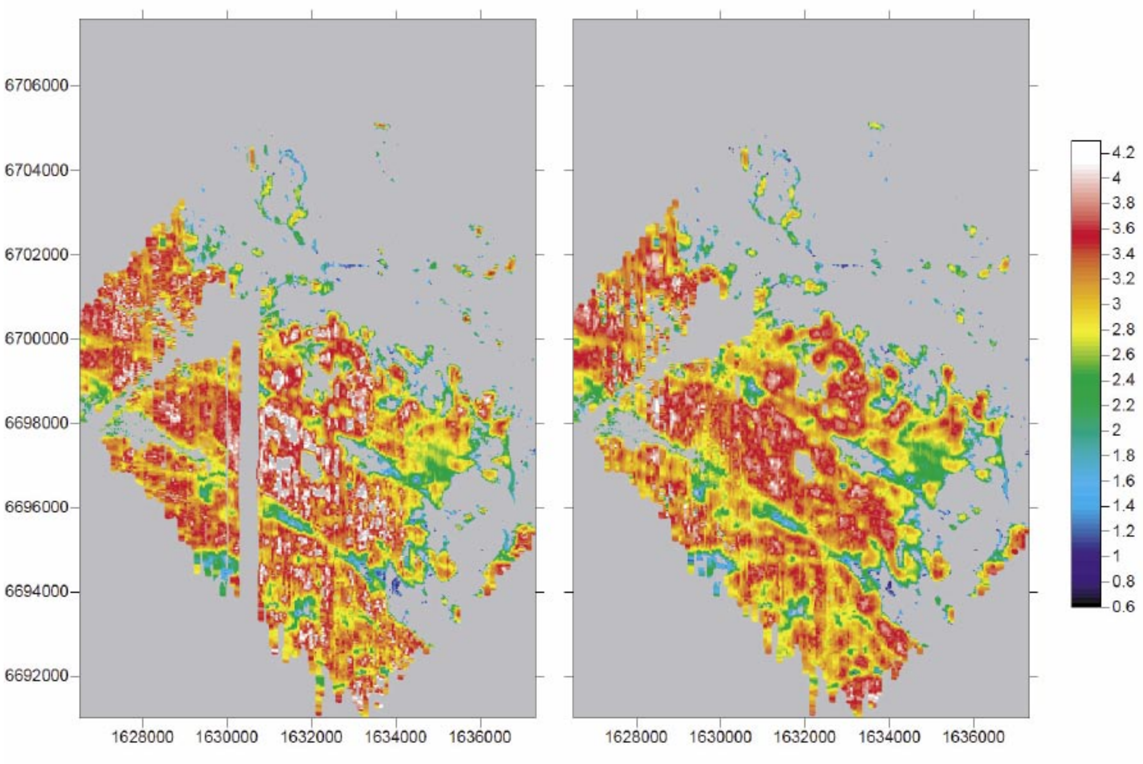

Figure 3-9. *Maps showing logarithm of apparent resistivity in Ω m for 7,001 Hz quadrature component (left) and 6,606 Hz quadrature component (right). Good data are missing for one flight for 7,001 Hz south of the Forsmark power plant.*

3.6 Compilation of a priori information

A priori information about layer parameters is used as constraints during inversion. The information is compiled into regular grids that describe the expected values of the model parameters over the area, based on the information available. The variances of the parameters are also estimated. Areas with poor coverage of a priori information will thus correspond to high variances. The a priori information is weighted with the inverse of the variance prior to inversion. This means that only very weak constraints will be active in areas with little a priori information.

3.6.1 A priori information over land areas

Soil cover resistivity

Information about soil cover resistivity can be extracted from the VES layered earth models /2/. The models provide information about the resistivity at the locations of the soundings but also information about what resistivity to expect for the most common soil types in the area. Information about soil types is available from detailed mapping that has been performed /11/. The soil mapping project did however not cover the entire survey area. Less detailed soil type information (e.g. wetlands) can be extracted from the topographic map.

Figure 3-10 illustrates the compilation of soil type resistivity information. Resistivity values are first interpolated through inverse distance weighting of the VES models. The variance estimations of these interpolated values are based on the rough expected spatial wave-lengths of resistivity variations. The average resistivity of the most common soil types can also be extracted from the VES models. Several soundings have been performed on coarse grained moraine, which is the most common type. A few soundings have also been performed on the clay-bearing moraine that occurs around Storskäret. Less information is available about the resistivity of other soil types, e.g. different types of bogs and wetlands. The resistivity of these has been assigned values based on experience from other work in Sweden. By assigning appropriate resistivity values to the different soil types a second map of expected resistivity values was produced (Figure 3-10). The variance estimates were based on the variance of VES models for a particular soil type. The topographic map was also used since the soil map did not cover the entire survey area. Forest areas were assigned the resistivity of the coarse grained moraine, arable land was assigned the resistivity of the clayey moraine and wetlands were treated as above. Some wetlands close to the sea near Kallrigafjärden showed very low apparent resistivity in the EM data. The apparent resistivity for the quadrature component of the highest frequency was therefore assigned as the soil cover resistivity for these areas. As a final stage the different grids were merged to one, where the resistivity value was assigned the value from the source with lowest variance. A slight smoothing was also performed to account for the fact that different soil types overlay each other.

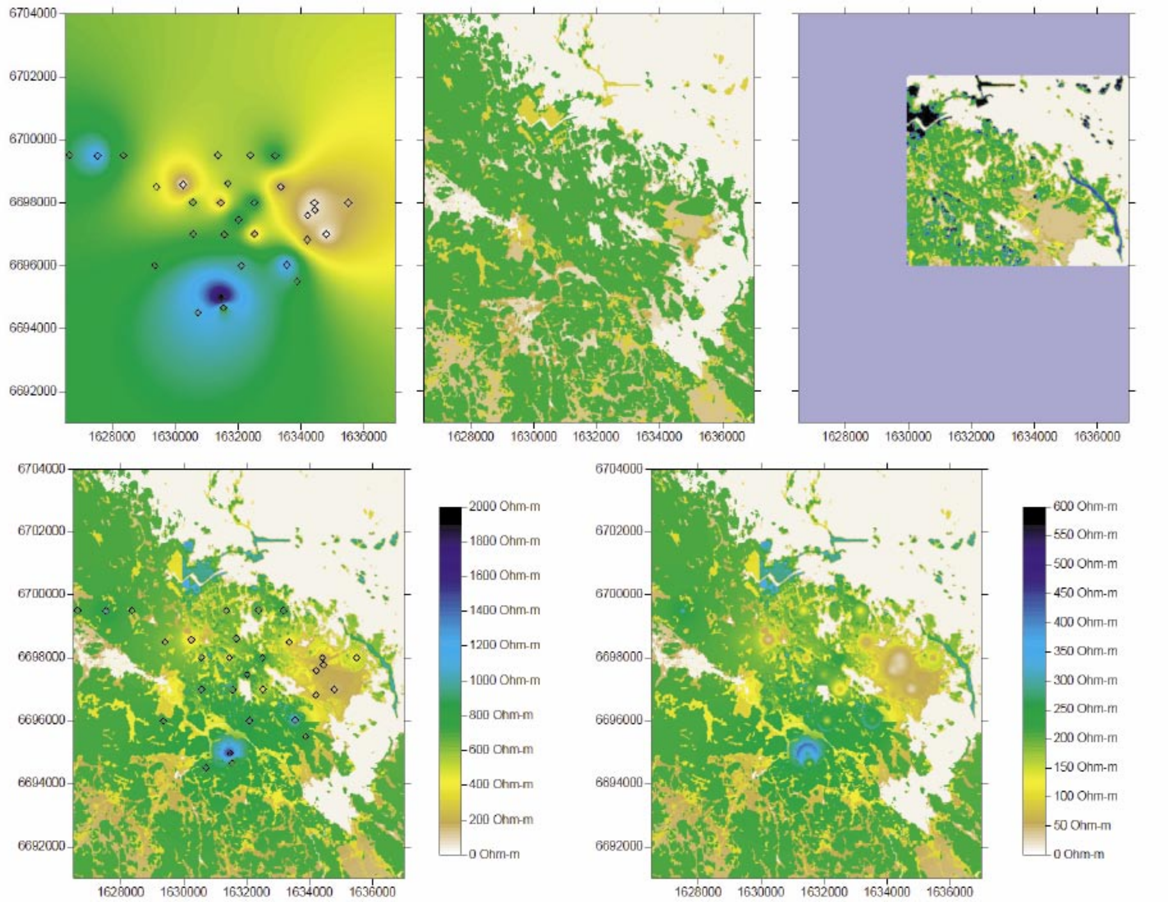

Figure 3-10. *Compilation of a priori information about soil cover resistivity. VES stations are shown on the two left maps as black symbols. Inverse distance interpolation from VES models (top left), assigned resistivities based on landcover on the topographic map (top centre), assigned resistivity based on soil type mapping (smaller area, top right) and merged information from the three sources (bottom left). The same colour scale applies to all these four maps. The map at the bottom right shows the estimated variance of the merged data (separate colour scale).*

Soil cover thickness

Information about the soil cover thickness is available at a number of drilling locations. The soil cover thickness has also been estimated at the VES sounding stations. The cover thickness is also known to be zero at rock outcrops.

Figure 3-11 illustrates the compilation of soil cover thickness information. Thickness values are first estimated through weighted inverse distance interpolation of the drilling data and the VES models. The bedrock topography of the Forsmark area is quite undulating so this interpolation gives reliable results only close to the original data points. The interpolated depths are thereafter merged with rock outcrop information. Areas at some distance from any drillhole, VES station or outcrop are then simply given a constant value with high variance.

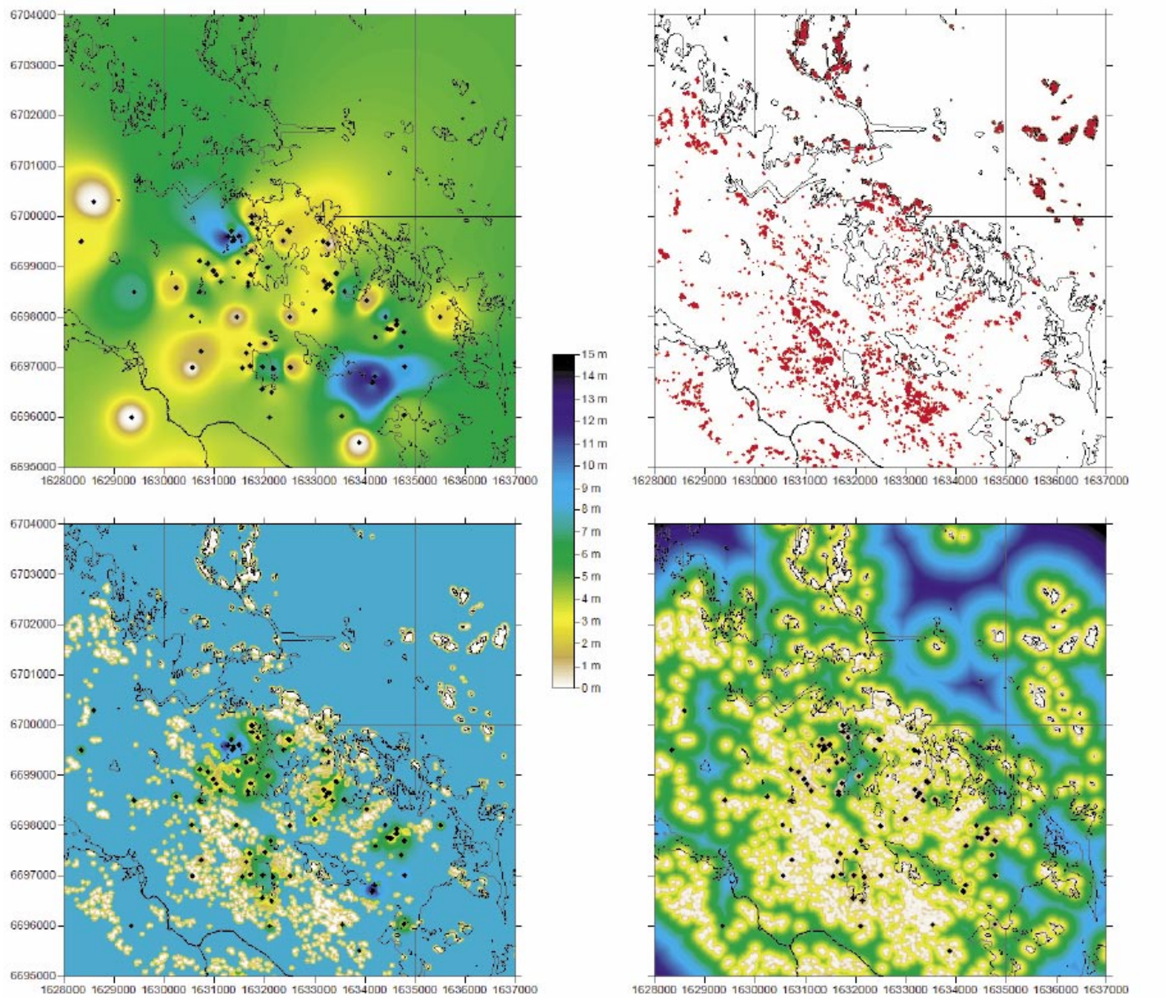

Figure 3-11. *Compilation of a priori information about soil cover thickness. Inverse distance interpolation from drilling data and VES models (top left), rock outcrops in red (top right), merged information (lower left) and estimated variance (lower right) The same colour scale applies to all maps. Drill holes and VES stations are shown with black symbols.*

It can be seen in Figure 3-11 that some areas with outcropping rock have been assigned non-zero cover thickness in the merged data. This is because some nearby drill hole or VES station has a non-zero thickness. The footprint of the EM-system is larger than the short wave-lengths of the soil cover lateral variations so the inversion result should be considered as an average over the footprint. A location with outcropping rock might thus be assigned a non-zero thickness value.

Bedrock resistivity

The bedrock resistivity information available is from VES stations and X-configuration resistivity measurements /2/. The bedrock resistivity was estimated from this information through weighted inverse distance interpolation. After running the inversion it was however evident that the bedrock resistivity was poorly constrained. Assuming that the bedrock can be regarded as a homogeneous half-space at rock outcrop locations, the apparent resistivity for such areas can be regarded as reasonable estimates of the bedrock resistivity. The interpolated values were therefore replaced by frequency 2 (6,606 Hz) apparent resistivity values at rock outcrops. It should however be noted that the minor outcrops are smaller than the footprint of the EM system and apparent resistivity values for such positions will be affected by the surrounding soil cover. Some outcrop data might also be affected by 2D- or 3D-structures or by noise from power lines. The results can be seen in Figure 3-12. There appears a discrepancy between the interpolated values and the apparent resistivity data. The variance of this a priori data set has been set rather high so that the inversion will not be severely affected by wrong estimations.

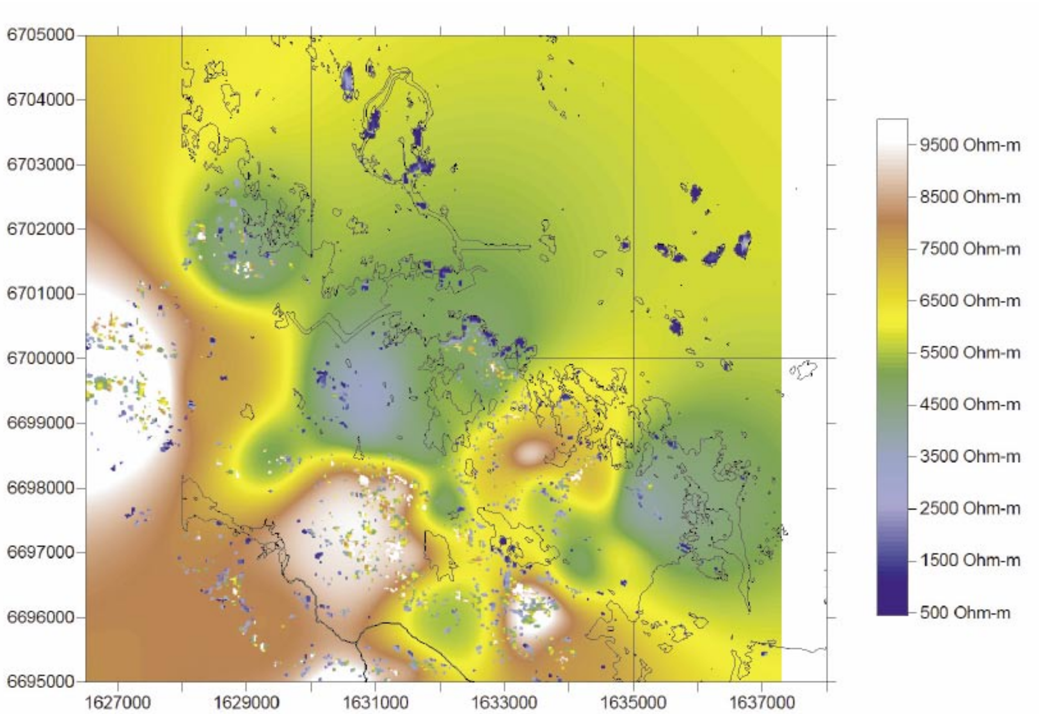

Figure 3-12. *Compilation of a priori information about bedrock resistivity. Interpolation has been performed on resistivity estimates from VES models. Apparent resistivity values of frequency 2 (6,606 Hz) have been used at rock outcrops.*

3.6.2 A priori information over sea areas

Water depth

Bathymetric measurements within the SKB site investigation program have been undertaken in the area /12, 13/. These data were however not available when this work was performed. Some water depth data from a gravity survey on the sea ice were used instead /9/. Water depth data could also have been retrieved from sea charts. However, the inversion was tested without such data and the results were so good that no effort was made to include sea chart data in the process. The relation between water depth and the distance from nearest land was investigated (Figure 3-13). A correlation can be seen in the figure even though the scatter is quite large. The relationship was modelled with a second degree polynomial through the origin.

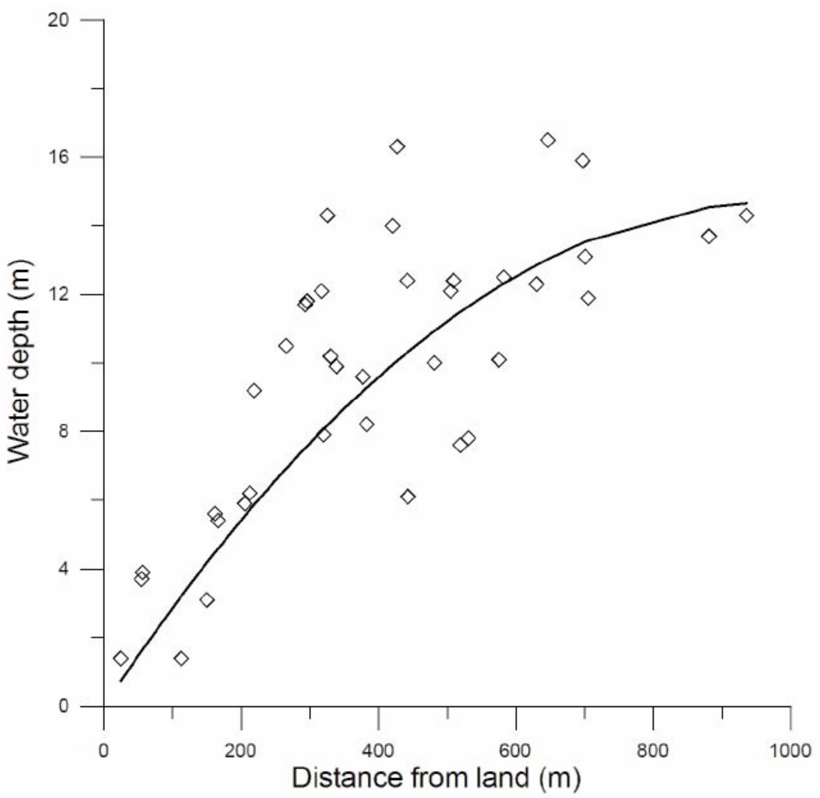

Figure 3-13. *Relationship between water depth and the distance from nearest land for the water depth data available at the time of this work. The trend in the data has been modelled by a second degree polynomial through the origin: Depth = 0.0319·distance + 1.55·10*$^{-5}$ *·distance*^{2}*.*

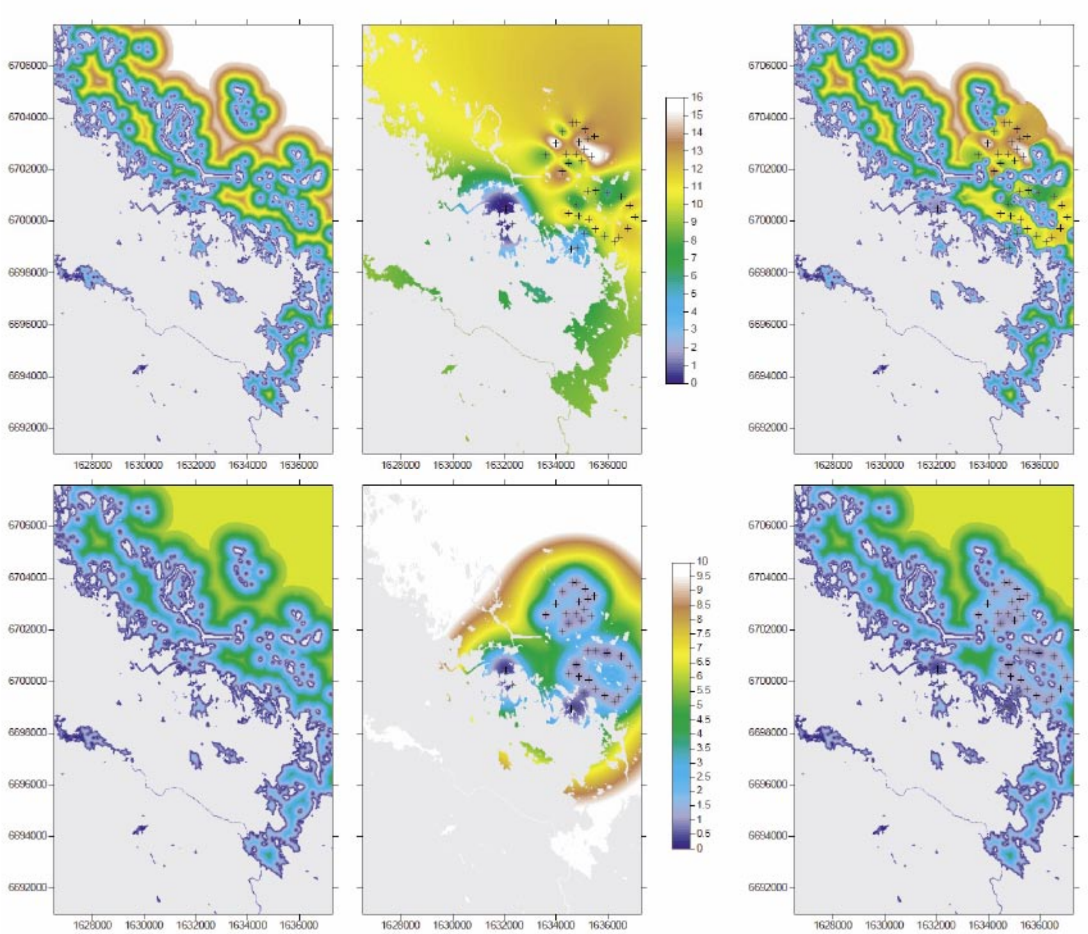

Figure 3-14. *Compilation of a priori information about water depth. Depth estimated from distance to nearest land (top left), inverse distance interpolation (top centre) and merged grids (top right). The bottom row of maps shows the estimated variance of the upper row of maps. The same colour scale applies to all maps in each respective row.*

The water depth for the sea area calculated according to the polynomial shown in Figure 3-13 can be seen in Figure 3-14. The depth was also calculated by inverse distance interpolation from the water depth data. The two grids were merged, taking into account the estimated variance of each, resulting in a final a priori estimation of water depth for the area. Note that depths have been estimated in the lakes. However, the lakes are considered to be too small for reliable inversion results and no inversion has been carried out there.

3.7 Inversion of land data

The levelled field components and the altimeter data were interpolated to regular grids with the same node spacing (25 m east-west, 10 m north-south) as the a priori information. Nearest-neighbour interpolation was used to avoid mixing of different survey line data with each other. The easting and northing coordinates were interpolated in the same way, resulting in grids that for a certain grid node hold the information of the levelled data, the altimeter value and the original location of the measurement. The areas corresponding to the sea and other water bodies were blanked out. The inversion was carried out with the height above ground as a free parameter but constrained by the altimeter reading. A variance was specified for the altimeter data that accounts for some possible errors due to faulty calibration and reflections from e.g. dense vegetation.

The inversion started at seed-points corresponding to the locations where a priori information was available, i.e. drill holes and VES stations. The inversion then proceeded to grid nodes at gradually larger distances from the seed points by a random search procedure (Figure 3-15). For each new inversion, the possibility of neighbouring nodes already being solved was checked. If solved nodes were found, those solutions were used as constraints when solving the new node. This constraint was weighted by the inverse of its residual error. The use of neighbouring nodes as constraints is applied to get lateral consistency in the output model.

The output of the inversion was grids of solved parameters for the layered earth model and the measurement height above ground. These data were then converted into a table format and new grids were interpolated using the inverse distance method. This last procedure was undertaken to get a smoother representation of the layer parameters. Additional smoothing was performed with a 3×3-node convolution filter.

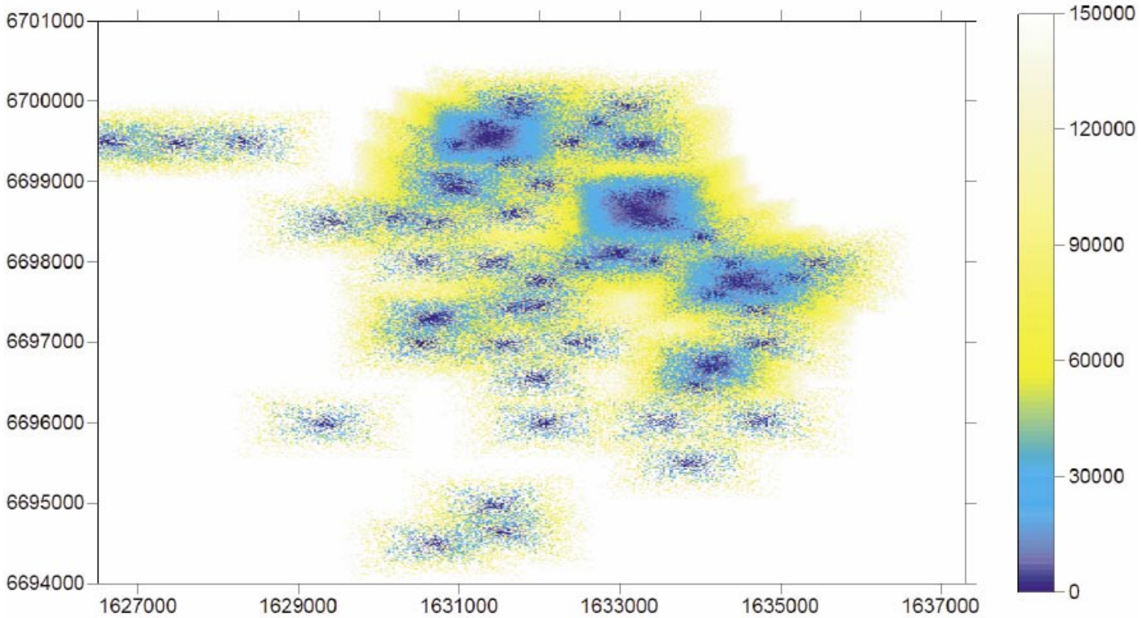

Figure 3-15. *Map of the central part of the survey area showing the progress of the inversion. The colour scale corresponds to the order in which the nodes were processed. Inversion starts at seed-points (drill holes and VES stations) and continues outwards by random search for unsolved nodes.*

3.8 Inversion of sea data

The inversion of sea data was carried out in a corresponding way as for the land data with the difference that land areas were blanked in the data files. Lakes were also blanked out since all lakes in the area were considered too small for reliable inversion results.

The original altimeter data and the measurement height from the inversion output can be seen in Figure 3-16. The two maps are more or less identical. Some minor differences can be seen along the shore line which might be an effect of the deviation from the assumed one-dimensional model. The good correspondence is in agreement with correct gain and phase calibration of the EM data and also of correct altimeter calibration.

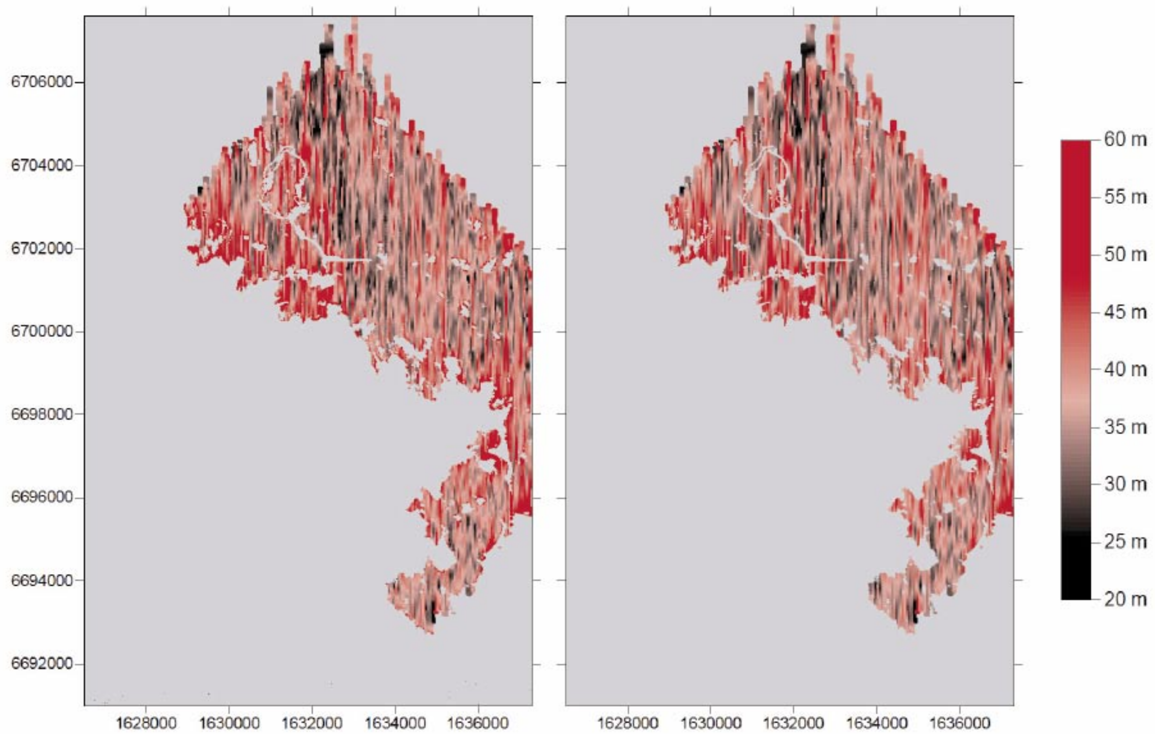

Figure 3-16. *Inverted height of the measurement system for sea areas (left) and altimeter data (right).*

4 Results

4.1 Inversion results for land areas

4.1.1 Soil cover

The parameter that can be resolved by the inversion that relates to the soil cover is the conductance of the upper layer in the model (thickness to resistivity ratio). The resistivity or thickness cannot really be resolved individually. Instead estimates of these parameters rely on good a priori information. The integrated conductance of the soil cover from the inversion process can be seen in Figure 4-1.

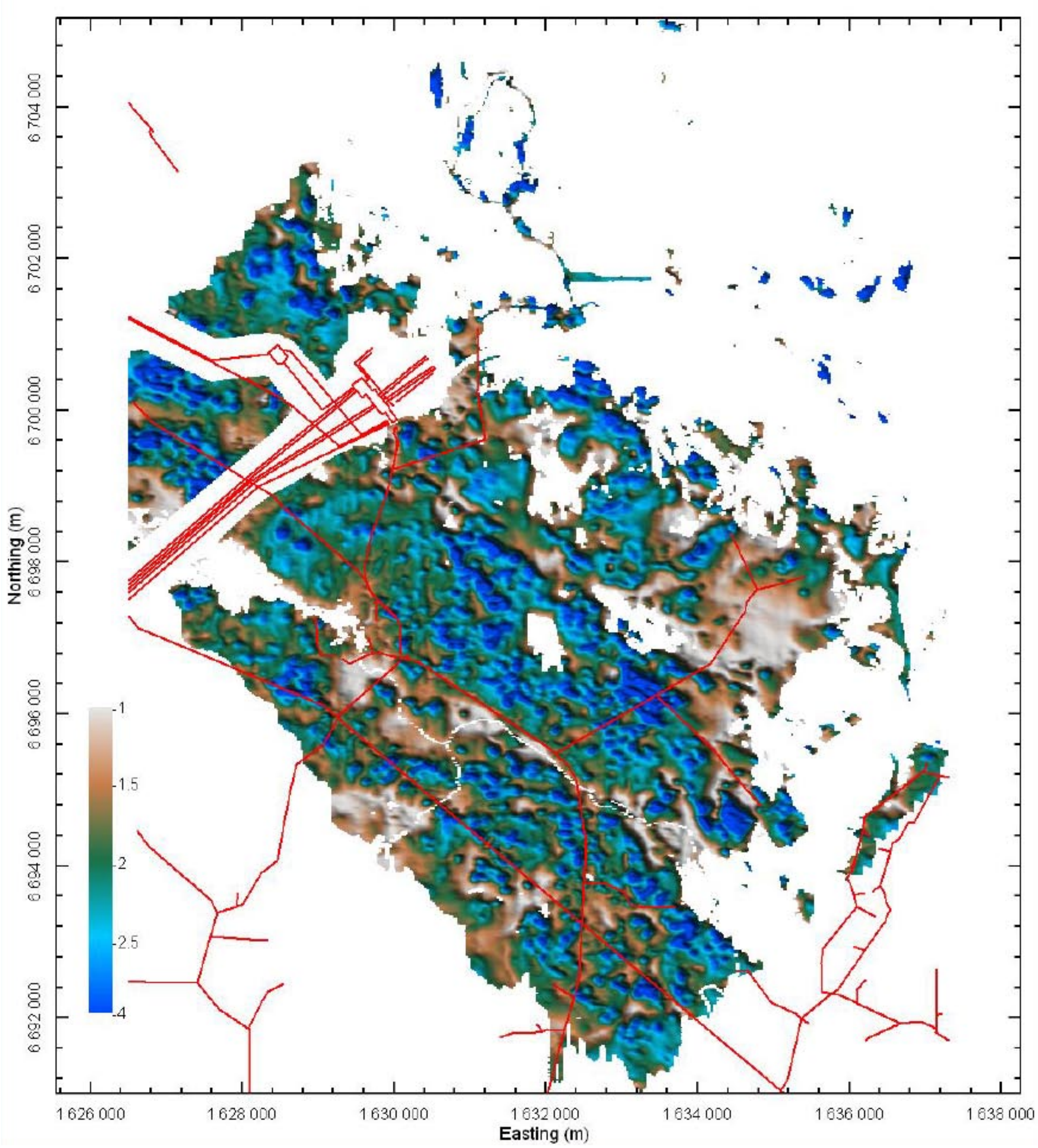

Figure 4-1. *Inversion output of logarithm of soil cover conductance in Siemen. Areas close to major power lines have been blanked out. Power lines are shown with red lines.*

The inverted soil cover resistivity and thickness can be seen in Figures 4-2 and 4-3 respectively. The resistivity results are in fairly good agreement with the a priori information. The inversion has produced obviously erroneous results at a few locations. Such locations occur along the coast line, at small islands and close to the power plant.

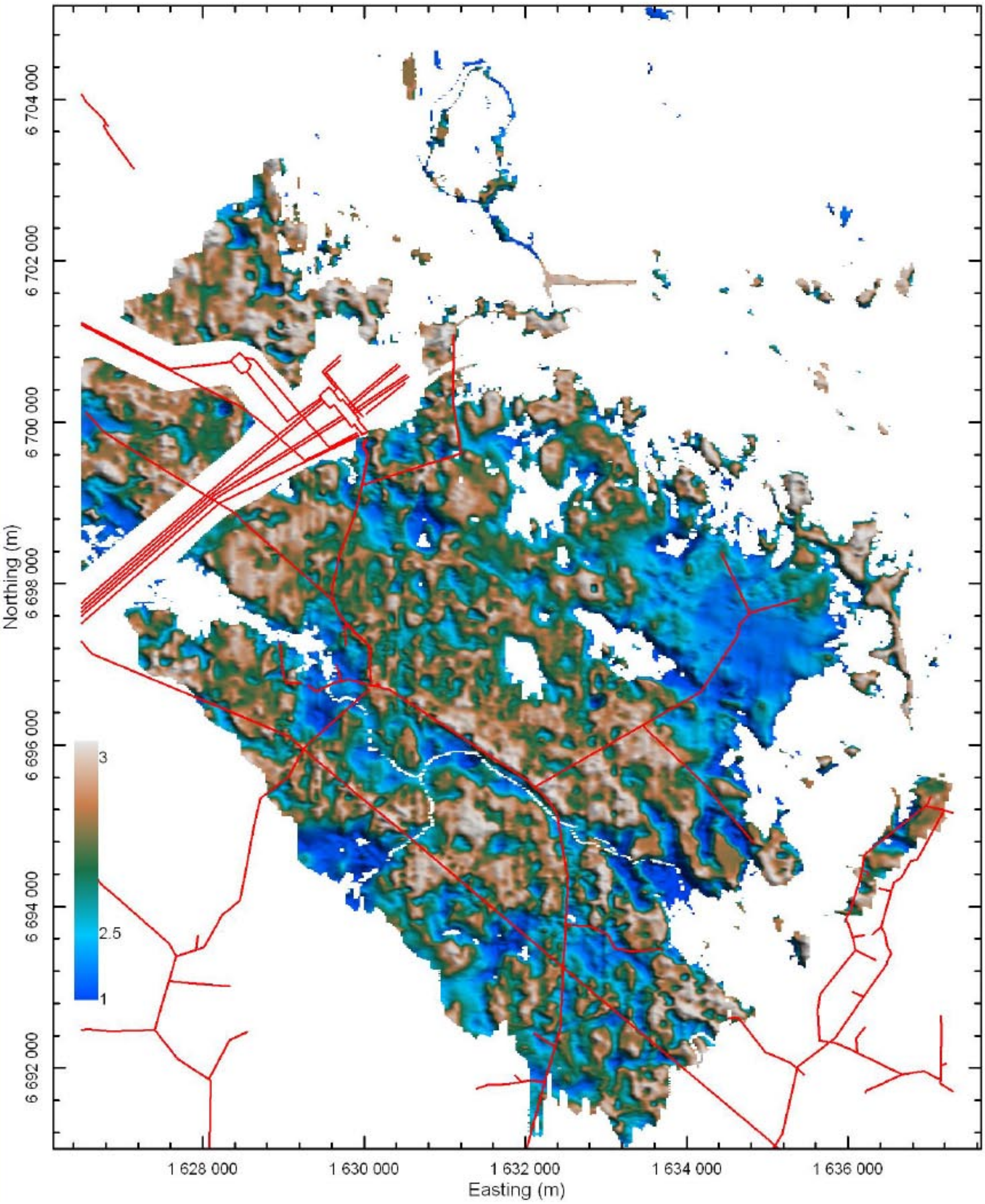

Figure 4-2. *Inversion output of logarithm of soil cover resistivity in Ωm. Areas close to major power lines have been blanked out. Power lines are shown with red lines.*

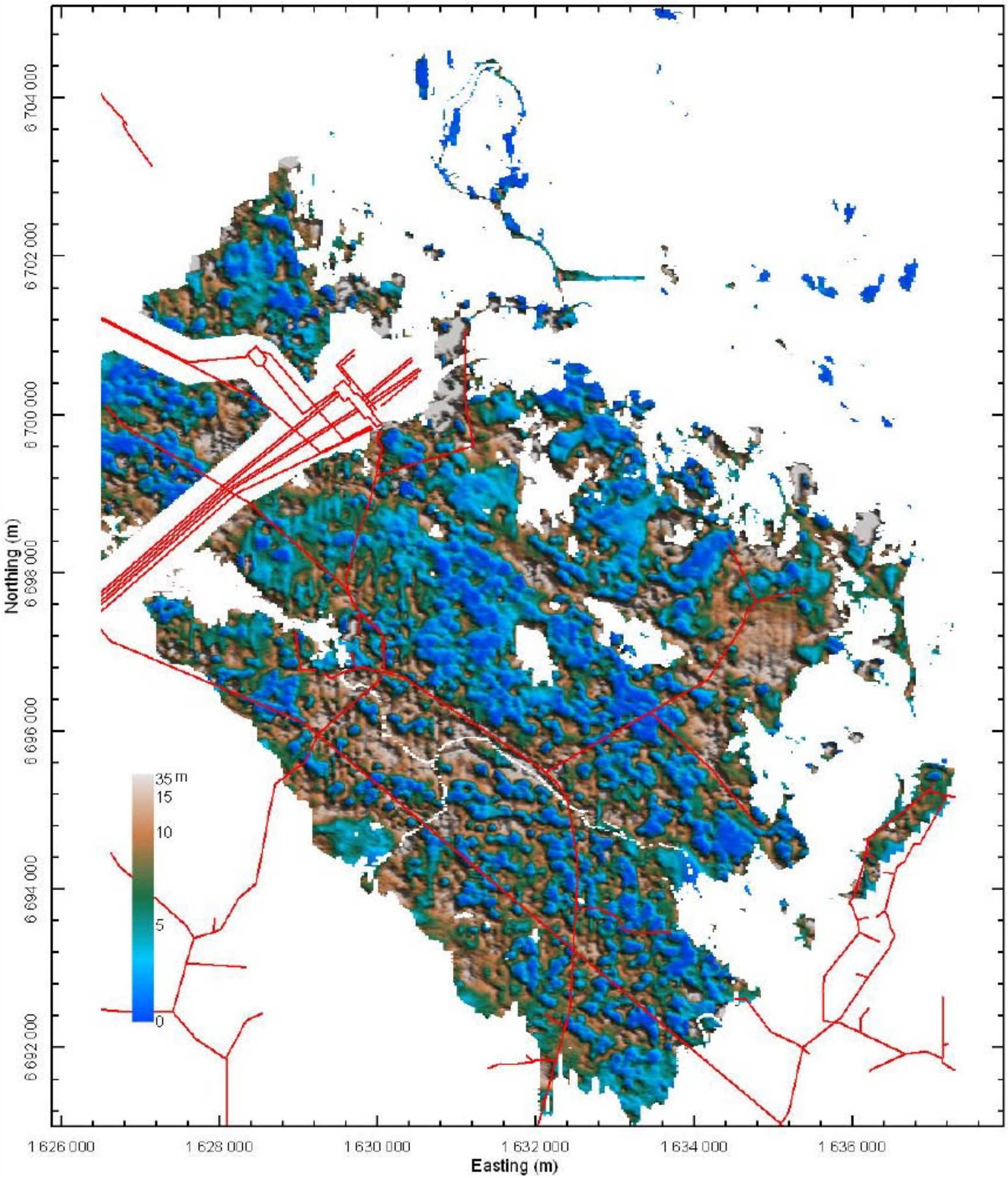

Figure 4-3. *Inversion output of soil cover thickness. Areas close to major power lines have been blanked out. Power lines are shown with red lines.*

4.1.2 Bedrock

The inverted bedrock resistivity can be seen in Figure 4-4. Most of the area show high resistivities typical of crystalline rocks. The inversion output seems to be biased toward low values at some areas of high conductance in the soil cover. It thus seems as the resolution of the bedrock resistivity is poor for such areas and the results might not be correct. Low resistivities can also be seen along powerlines and close to the coast line. Such results may also be erroneous due to false anomalies caused by the power-lines and deviations from the layered earth model at the shore line. It is also possible that the bedrock resistivity is low close to the shoreline due to influence of saline groundwater at moderate depth. Such effects on the resistivity have however not been confirmed. Low bedrock resistivities that cannot be explained by noise or poor resolution can be seen at two locations. One such location is east of Johannisfors where ultra-mafic rocks are known to occur. Rock samples from this rock type have shown low resistivities /10/ and those results seem to be compatible with the bulk properties indicated by the inversion. Low resistitity can also be seen in an area south of the Forsmark power plant.

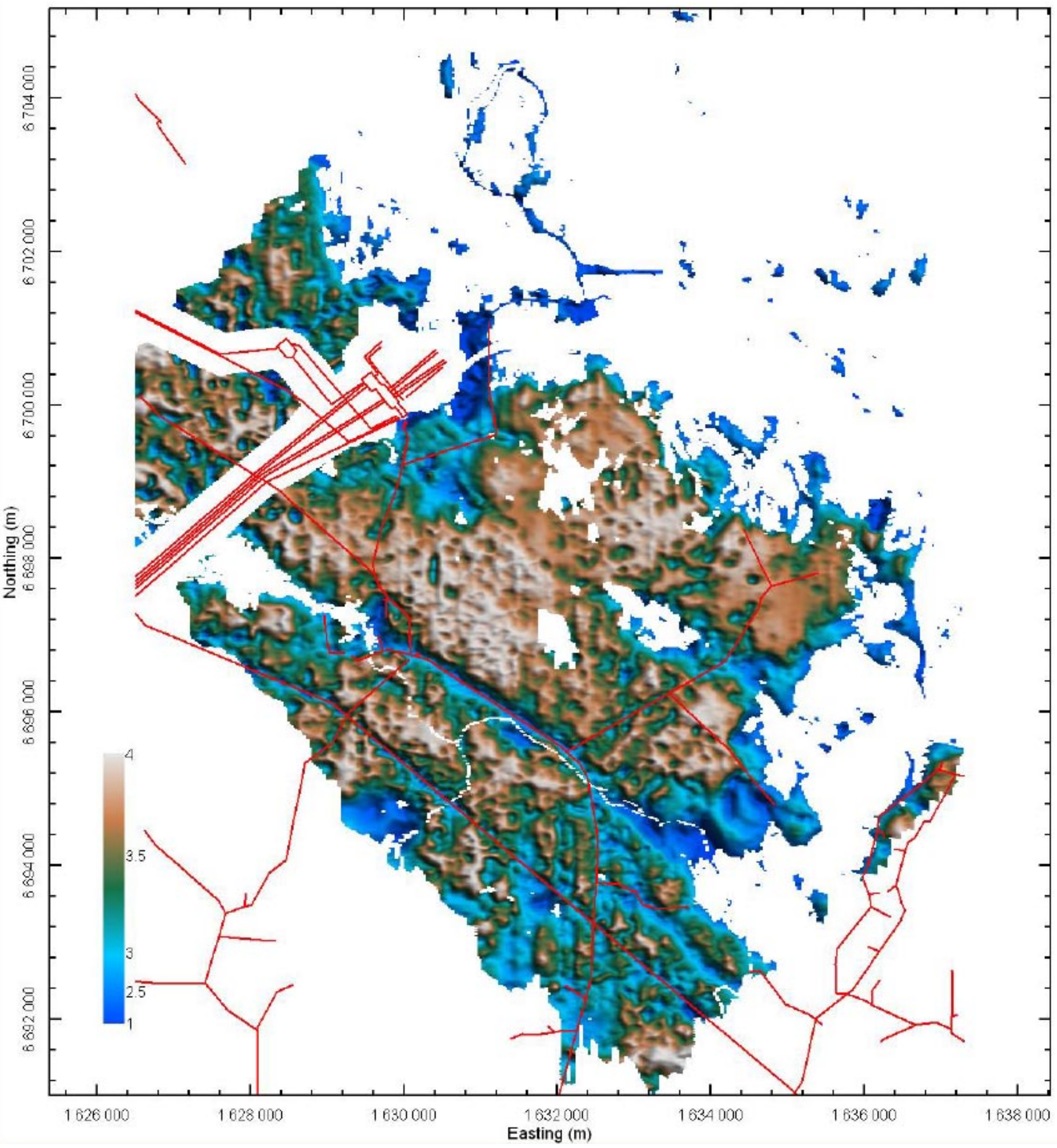

Figure 4-4. *Inversion output of logarithm of bedrock resistivity in Ωm. Areas close to major power lines have been blanked out. Power lines are shown with red lines.*

4.2 Inversion results for sea areas

4.2.1 Water depth

The inverted water depth can be seen in Figure 4-5. The inversion results are very good although stripes along the profile direction can be seen. Several lineaments can be seen in the sea-floor topography and the results have been used in the integrated lineament interpretation of the area /14/. Comparisons with known water depths indicate that the inversion results are quite accurate.

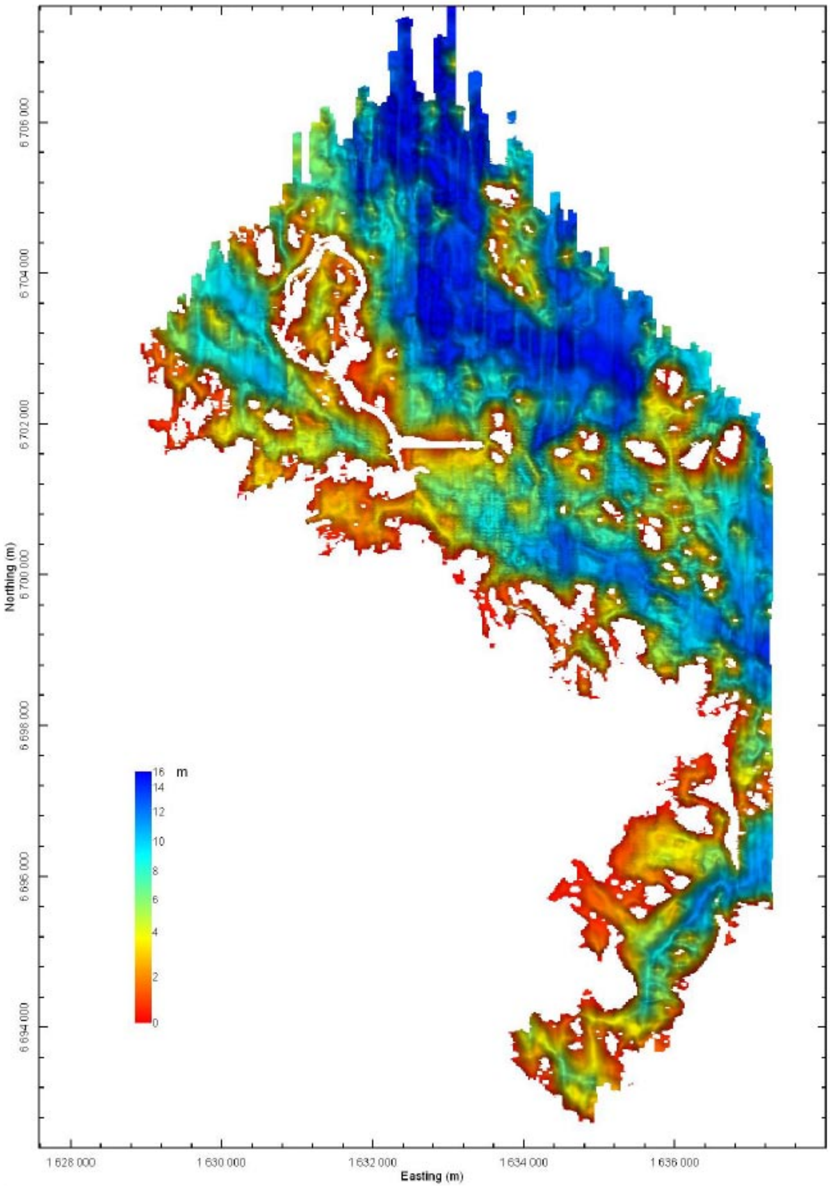

Figure 4-5. *Inversion output of sea water depth. Permission to publish: Sjöfartsverket 010305-04-17297:22.*

4.3 Data delivery

The following data have been delivered to SKB: Levelled profile data, grids of compiled a priori information, grids of inversion output, inversion output in table format and georeferenced maps.

The SICADA reference to the present activity is field note Forsmark no 406.

5 Conclusions

The inversion could be carried out in a successful manner but a few things need to be pointed out concerning the results.

The soil cover parameters cannot be resolved individually. The well resolved parameter is the conductance of the soil cover (thickness to resistivity ratio). The determination of thickness and resistivity is relying upon good a priori information but some parts of the survey area lack such information. If new information becomes available it will be very easy to make new estimates of the soil cover parameters since the only thing that has to be done is to recompile the a priori data grids and then run the inversion once more.

The soil cover data can be used as a starting point for the creation of a soil depth model of the Forsmark area. Additional information must however be integrated and the model needs to be verified by field investigations.

The bedrock resistivity seems to be difficult to resolve under conductive soil cover. This is partly due to the nature of the EM response of such resistivity structures and partly due to the fairly poor data quality of the EM data from Forsmark. The low frequency components were severely affected by noise from the major power lines and this has reduced the methods ability to resolve the bedrock resistivity in a correct way. Reasonable estimates of bedrock resistivity have however been obtained for areas with less conductive and/or thinner cover.

The water depth inversion was quite successful. This is perhaps not surprising as the EM response over the well conducting sea water is quite strong. The results have in some areas filled gaps that are not covered by any sonar bathymetric data.

The results gained in this work would not have been possible to obtain without the use of a priori information for calibration and levelling of the data and as constraints during inversion.

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