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Lake Muir SkyTEM Airborne EM Data

Phase 2-Data processing and inversion results

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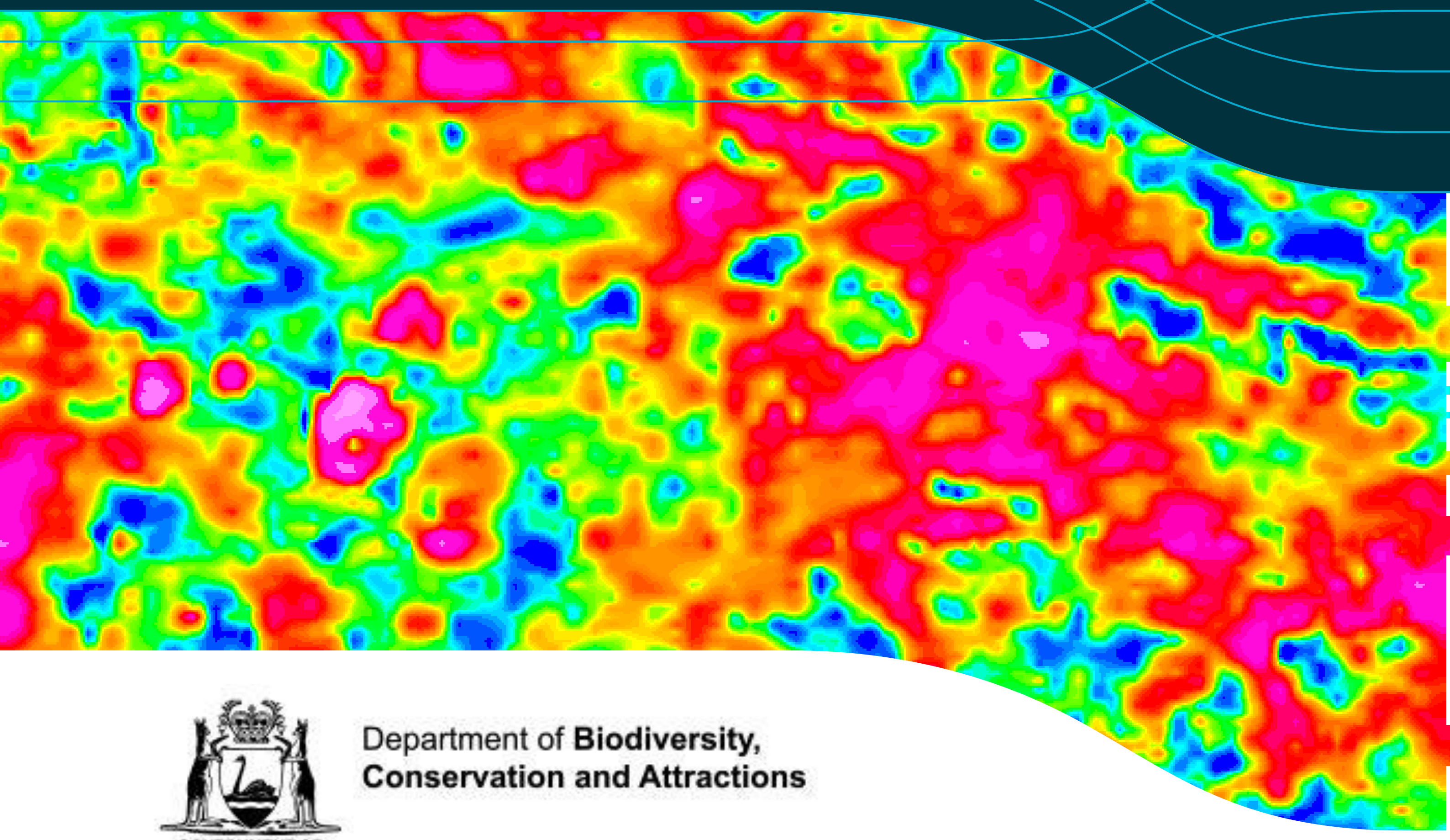

GOVERNMENT OF WESTERN AUSTRALIA

Department of **Biodiversity, Conservation and Attractions**

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Acknowledgments

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Executive summary

The West Australian Government through the Department of Biodiversity, Conservation and Attractions (DBCA) are engaged in research over the Muir-Byenup area, focusing on the peat wetlands present which tend to be sustained by shallow (0-15 metres below ground level) groundwater flow systems. They have reported that shallow stratigraphy appears to be highly variable near the wetlands, with associated hydraulic properties potentially changing at the metre or two metre scale. Consequently, there is an expectation that the ground electrical conductivity would also vary at a similar scale. To assist in the management of these peat wetlands, the Department acquired SkyTEM airborne electromagnetic (AEM) over the region.

CSIRO revisited the original analysis and inversion of the Muir AEM data set and undertook a second phase of processing and inversion of these data to improve the definition of the near-surface conductivity structure. This report describes that processing and inversion. Given that the SkyTEM survey was flown with a line spacing between 100 and 300m, a spatially constrained inversion (SCI) was originally employed. A quick assessment of the data processing (not the inversion results) identified several issues with the data that could have an impact on the subsequent models from their inversion. The issues identified included insufficient altitude processing – leaving data spikes in the altitude data set; excessive trapez filter width for high moment – potentially removing, over smoothing or suppressing signal from depth; trapez sounding distance (time between soundings in averaged data) – subsampling of the data (soundings) with the result that information of relevance, particularly in the near surface might be missed; and a failure to fully remove the effects of coupling – as a result of cultural noise in the area (powerlines, houses etc.) The reprocessed data were then re-inverted using a starting model with emphasis on the near surface. A new set of interval conductivities, and conductivity depth sections were produced.

1 Introduction

1.1 Background

The West Australian Government through the Department of Biodiversity, Conservation and Attractions (DBCA) are engaged in research over the Muir-Byenup area, focusing on the peat wetlands present which tend to be sustained by shallow (0-15 metres below ground level) groundwater flow systems. They have reported that shallow stratigraphy appears to be highly variable near the wetlands, with associated hydraulic properties potentially changing at the metre or two metre scale. Consequently there is an expectation that the ground electrical conductivity would also vary at a similar scale.

With this understanding, and an expressed desire to employ existing SkyTEM airborne electromagnetic (AEM) data to assist in the management of these peat wetlands, CSIRO revisited the original analysis and inversion of the Muir data set and undertook a second phase of processing and inversion of these data *to improve the definition of the near-surface conductivity structure*. This document sets out the findings of that review and describes the results from the re-inversion of the SkyTEM data set. A summary of the SkyTEM AEM system is also presented to provide additional context for the discussion on the processing, inversion and the resulting outputs.

1.2 Lake Muir SkyTEM AEM Survey

The WA Government Department of Environment and Conservation (now DBCA) SkyTEM^{312} survey over Lake Muir and surrounds was undertaken between 22nd June and 9th July, 2008, employing the dual moment SkyTEM AEM system (Reid et al. 2008). Over 3096 line kilometres of data were acquired along lines shown in Figure 1. Average ground clearance for the completed survey was 34.5 m, given the presence of tall trees in the area. Line spacing for the main survey was 300m, orientated N-S, with two small areas of infill, which reduced the line spacing to half that or less (Figure 1).

1.2.1 The SkyTEM AEM system

The SkyTEM system is a time domain helicopter-borne electromagnetic system developed in Denmark in 2004 (see Sørensen and Auken 2004 and Halkjaer et al. 2006) for a more complete technical description). The system was originally developed for groundwater mapping purposes and in an Australian context the SkyTEM system has successfully been applied to mapping of alluvial aquifers, including buried palaeovalley systems, across Australia (see, for example, Viezzoli et al. 2009; Lawrie et al. 2010; Fitzpatrick et al. 2011, Davis et al. 2015, and Munday et al. 2016). The Lake Muir survey was amongst one of the early SkyTEM surveys ever undertaken in Australia.

The SkyTEM EM system is carried as a sling load towed beneath a helicopter (Figure 2). It has a six-sided transmitter loop mounted in a lightweight frame. The system is capable of operating in a dual transmitter mode, low moment (LM) and high moment (HM) and for the Lake Muir survey, the survey all data was acquired using interleaved low and high moment transmitter modes with two different base frequencies (222Hz - low moment; 25Hz - high moment) (see Table 1).The low moment mode has a low current, high base frequency and a fast switch off providing early time data for shallow imaging, whereas the high moment has a higher current and a lower base frequency and thereby providing late time data for deeper imaging.

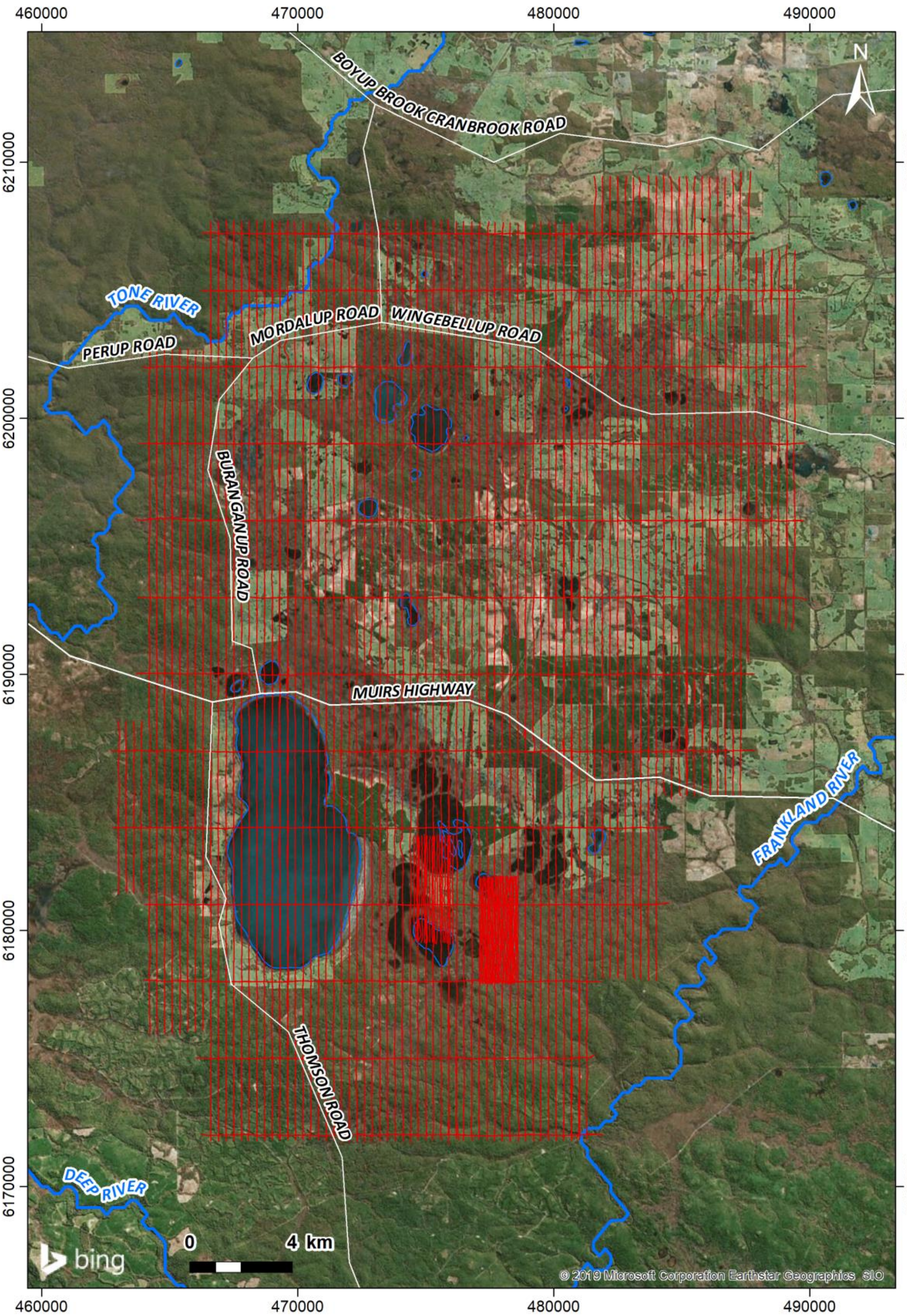

Figure 1 **Flight line map of the Lake Muir SkyTEM survey.**

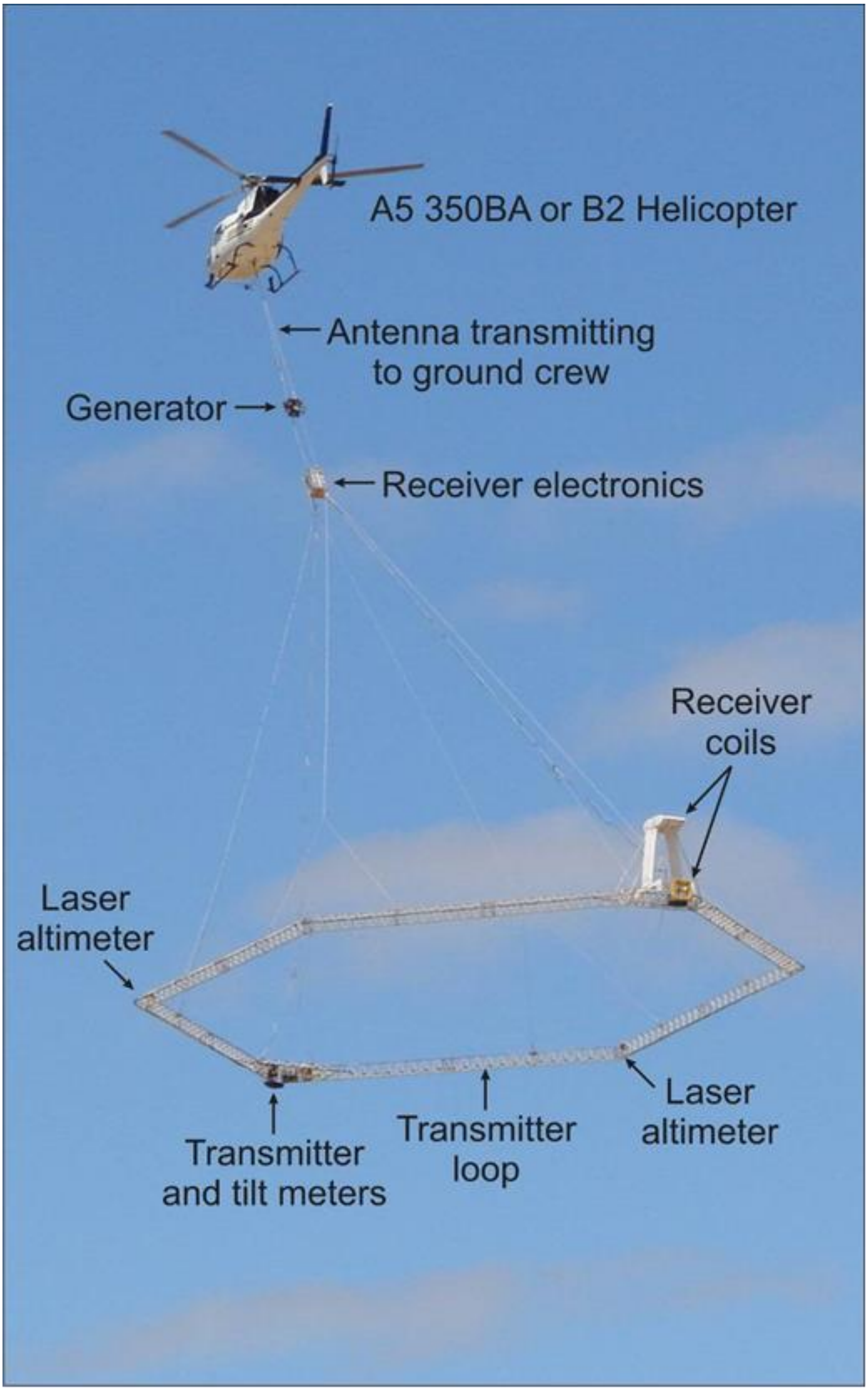

Figure 2 **The SkyTEM airborne electromagnetic system in flight mode**

Table 1 SkyTEM Transmitter specifications for Lake Muir Survey

EM Transmitter – High Moment	
Transmitter loop area	311 m^2
Number of transmitter loop turns	4
Average peak current	96.2 A
Peak moment	119,673 $A.turn.m^2$
Tx loop height (nominal)	30 m
Tx Waveform – High Moment	
Base frequency	25 Hz
Tx duty cycle	50%
Tx waveform	Bipolar
Tx on-time	10 ms
Tx off time	10 ms
Tx ramp time	37.2 s
EM Transmitter – Low Moment	
Transmitter loop area	311 m^2
Number of transmitter loop turns	1
Average peak current	41.3 A
Peak moment	12,844 $A.turn.m^2$
Tx loop height (nominal)	30 m
Tx Waveform – Low Moment	
Base frequency	222.22 Hz
Tx duty cycle	44.4%
Tx waveform	Bipolar
Tx on-time	1 ms
Tx off time	1.25 ms
Tx ramp time	8.68 s

The receiver loop is rigidly mounted at the rear and slightly above the transmitter loop in the near null position relative to the primary field, thereby minimising distortions from the transmitter (see Figure 2). Additional details are provided in Table 2 and the acquisition and processing report by Reid et al. (2008). Both X (inline) and Z (vertical) component data are recorded, but only the Z component data were used in the modelling of the Muir SkyTEM survey data.

Table 2 SkyTEM Receiver specifications.

EM Receiver	
EM Sensors	dB/dt coils
Rx coil effective area (Z and X)	31.4 m^2
Low pass cut-off frequency for Rx coils	450 kHz
Low pass cut-off frequency for Rx electronics	300 kHz
Z-component Rx coil position	
Behind Tx loop centre	12.62 m
Above plane of Tx loop	2.16 m
X-component Rx coil position	
Behind Tx loop centre	13.88 m
Above plane of Tx loop	0 m

The SkyTEM system is a calibrated system in the sense that is has been calibrated in the laboratory and standardised at the Danish National Reference Site ((Sørensen and Auken, 2004; Auken et al., 2009; Halkjaer & Reid, 2008; Foged et al., 2013), therefore arguably the system does not require any additional ground calibration procedures to derive relatively accurate conductivity models of the ground.

1.2.2 Processing and Inversion of SkyTEM data

Data processing

The aim of processing the AEM data is to prepare data for the data inversion. This involves data import, data corrections, filtering, and the culling and discarding of distorted or noise-filled data so they do not enter the inversion. Sources of noise in data include cultural infrastructure like powerlines, pipes, and buildings. The remaining data are then averaged spatially using trapezoid filters, which are designed to increase signal to noise levels without compromising lateral resolution of conductivity changes.

It has been demonstrated that failure to remove data affected by infrastructure, or noise from other sources, maps directly into the model space and affects the derived inversion results (Vezzoli et al. 2013). The consequences can lead to low confidence in the derived conductivity models in general, an overestimation of the depth to bedrock, or the base of aquifers, or suggestions of false barriers that may impede groundwater movement.

Data inversion

One of the primary objectives of the Lake Muir AEM survey was to map and interpret the spatial variations in the conductivity, particularly those associated with the near surface. Although measured AEM data can be imaged by gridding the raw window/time channels, where early time channels normally are associated with near surface and later time channels with greater depths, this is not necessarily always the case. Raw measured data are as such not a direct representation of the depth, but rather of a slice in time. Therefore, this kind of output can be useful for a quick overview of the distribution of more conductive vs more resistive areas, but information about the distribution of conductivity with depth cannot be inferred. The measured AEM decay curves can however, be converted through an inversion or transformation of the data to provide information about the conductivity distribution with depth.

Inversion of AEM data requires information about the characteristics of a specific AEM system such as time gates, waveform, current, filters etc. as an inversion is an iterative process of minimising the misfit between forward modelled responses (using these system specifications) from an electrical earth model and the measured AEM response, by changing the parameters of the earth model until an acceptable misfit is obtained. However, the result obtained from an inversion of AEM data is not a unique result as several conductivity-depth models are usually able to fit the data within the acceptable range of error. This non-uniqueness emphasises the need for verifying the inversion results by independent information such as drill-holes or, for example, other ground geophysical measurements.

The workflow for data processing and inversion of SkyTEM data is summarised in Figure 3.

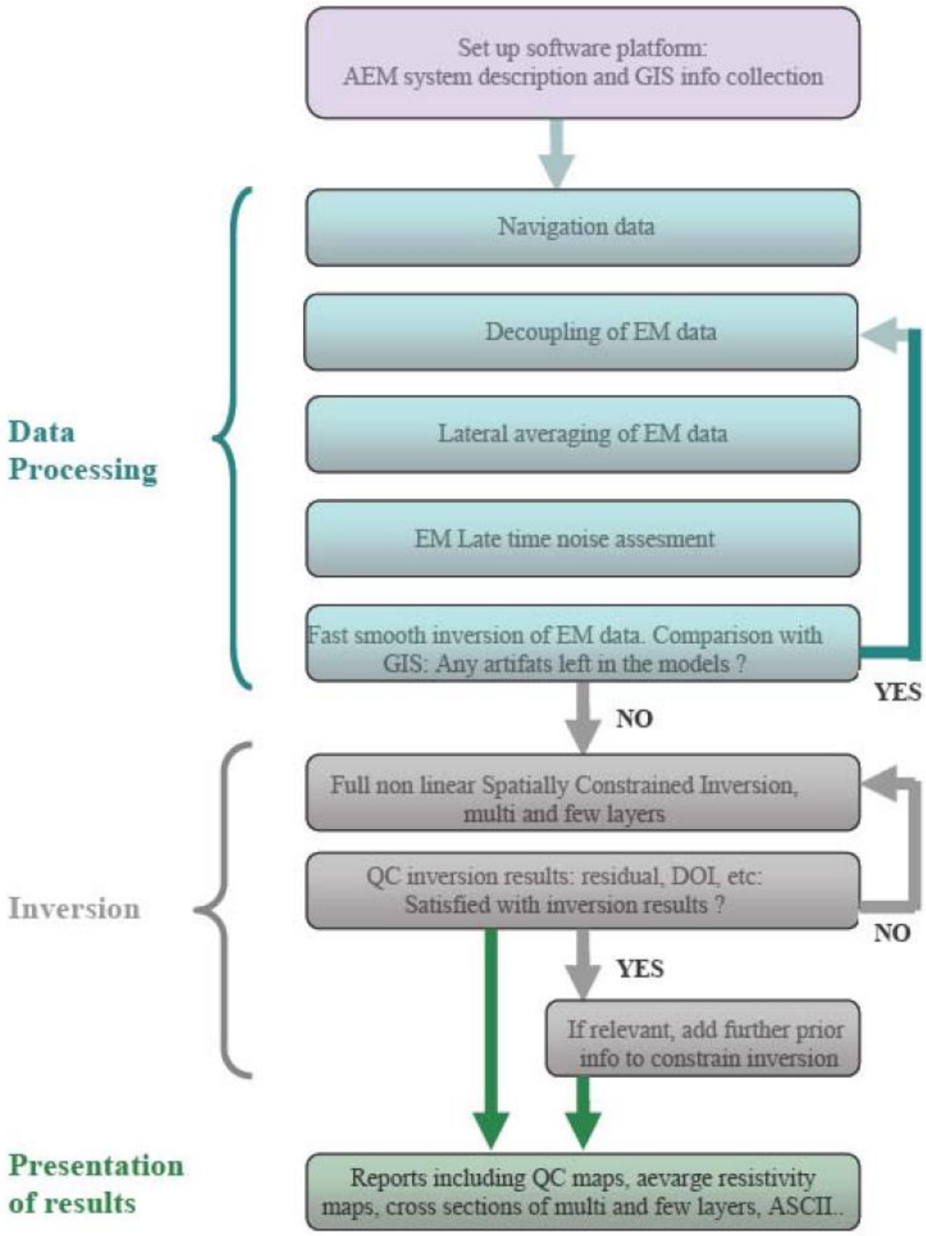

Figure 3 Workflow for the data processing and inversion of SkyTEM data (Source Aarhus Geophysics).

Inversion model - Spatially constrained inversion (SCI)

The Muir AEM survey was originally inverted using a smooth layered model consisting of 20 layers with fixed thicknesses, often increasing with depth. The inversion had constraints that were adjusted to allow for varying degrees of change in conductivity of one layer to the next. The large number of layers and the gradual change in conductivity for the smooth type of model makes the resulting conductivity models appear continuous. This in turn can make it difficult to pick layer boundaries as these may appear rather diffuse.

Given that the SkyTEM survey was flown with a line spacing between 100 and 300m, a spatially constrained inversion (SCI) (Viezzoli et al. 2008, Viezzoli et al. 2009)) was employed. The spatially constrained inversion uses a Delaunay triangulation to connect soundings both along lines and across lines through constraints. Obtaining models that honour information from along and across lines can result in a smoother appearance of the conductivity distribution as information is carried across from lines. The constraints in the Delaunay triangulation are given a weight according to distance, so that soundings closer together are more tightly constrained, and soundings far from each other are not linked at all.

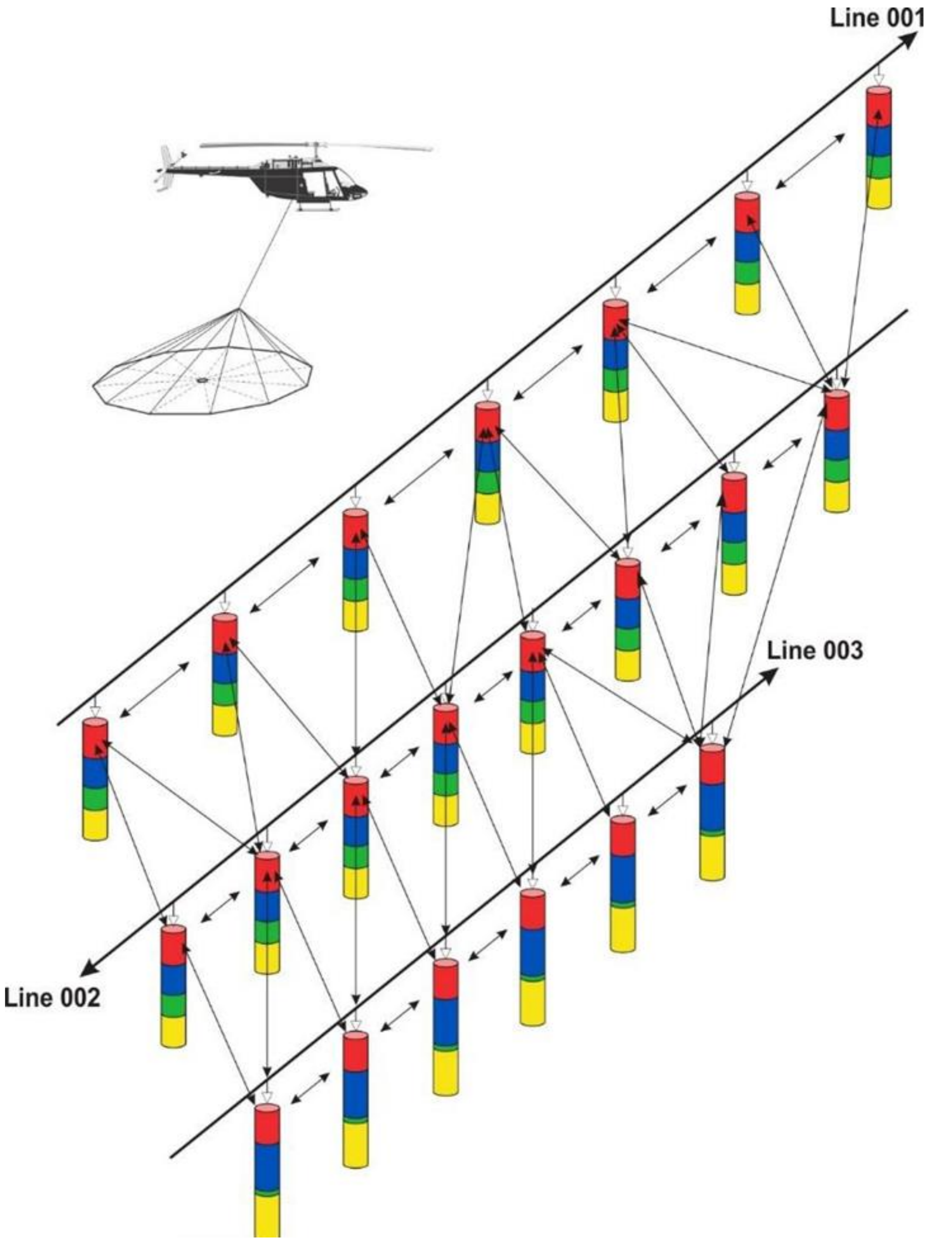

Figure 4: Schematic overview of the process of allowing prior information to migrate along and between a series of soundings acquired by an AEM system when they are inverted using the Spatially Constrained Inversion (SCI) procedure.

2 A review of the original processing and inversion of Lake Muir SkyTEM data

2.1 A review of the original processing and inversion

The original processing and inversion of the SkyTEM data acquired by DBCA over Lake Muir had the following objectives:

- Undertake a Spatially Constrained Inversion (SCI) (Viezzoli et al. 2008) of SkyTEM data for Lake Muir using the Aarhus Workbench software (Auken et al. 2015), and derive a set of products, including:
    - *A Depth of investigation map for the full survey*
    - *A map of "Thickness of conductive cover"*
    - *Grids of interval conductivities from the ground surface to depth*
    - *Conductivity-depth sections for each flight line acquired*

All the initial processing and inversion of the data set was undertaken in Aarhus Workbench (Auken et al. 2015). The Lake Muir Aarhus Workbench workspace contained SkyTEM data that had, as part of the initial work, been subject to data processing which included the application of automatic averaging trapezoidal filters and late time noise filters. The workspace also contained results from the inversion of these data using a Spatially Constrained Inversion (SCI). A quick assessment of the data processing (not the inversion results) identified several issues with the data that could have an impact on the subsequent models from their inversion.

Specifically, these were:

1. Insufficient altitude processing – leaving data spikes in the altitude data set
2. Excessive trapez filter width for high moment – potentially removing, over smoothing or suppressing signal from depth
3. Trapez sounding distance (time between soundings in averaged data) – subsampling of the data (soundings) with the result that information of relevance, particularly in the near surface might be missed;
4. Failure to fully remove the effects of coupling – as a result of cultural noise in the area (powerlines, houses etc.)

2.1.1 Altitude processing

The processing of the raw altitudes from the two laser altimeters fitted on the SkyTEM transmitter frame includes an automatic filtering and averaging process. Manual editing is often required to remove outliers, and to correct the altitude for areas where the automatic filter applied to the cloud data has been ineffective. For the Lake Muir workspace, the original processing of the altitude data appeared inadequate as it did not produce a smoothly varying altitude, but instead incorporated a lot of smaller outliers as illustrated in Figure 5. As the survey area contains a lot of forested areas, the altitude data may contain some canopy effects and in turn these will contribute to some of these small spikes in the data set. However, the large spikes identified in the data suggest that manual, or a revised automated filtering approach to remove them would improve the results of the subsequent inversion. In the first iteration of the SCI inversion applied to the Lake Muir data, and in subsequent inversions, many of these remain with consequences for the spatial continuity of the derived conductivity models.

2.1.2 Data processing

The automatic data processing that was applied to the original Lake Muir data set data included the application of an average trapez filter to aid removal of late time noise and choosing the sounding distance (distance between soundings) of the averaged data. Figure 6 shows the low moment amplitude responses for 3 minutes of data, where the sounding distance in the averaged data has been reduced to one sounding every 2.5 s which equates to one sounding every 55m. Whilst this reduces the overall number of soundings to be processed, making the inversion of the whole dataset quicker, it also has the effect of reducing data resolution (i.e. the resolution of lateral variability in the conductivity structure) at depth.

The trapez averaging width for the low moment appears to be adequate as lateral structure is left in the data. However, in the first phase of data processing, the late time noise has been removed from the raw amplitude data (responses shown in the top panel in Figure 6), whereas in normal data processing scenarios, this would have been kept in the raw data and removed from the average data i.e. after the trapez filter has been applied.

The trapez averaging filter for the High Moment data (Figure 7) appears a excessive particularly as structure has been removed from the amplitude responses. Decreasing the trapez filter width was thought to be beneficial, particularly as the data were not particularly noisy. Also given overlapping gates between the low and high moment, it would be desirable to set the trapez filter width to be the same for the overlapping gate times. Late time noise has been removed from the averaged data, but not for the low moment. This inconsistent approach to data processing was not ideal.

The review of the initial workspace indicated that there were some features in the data that could indicate coupling to anthropogenic features such as powerlines, buildings etc. These do not appear to have been cleaned from the data, even though their removal would potentially improve the interpretation of the resulting conductivity-depth models after inversion.

2.1.3 Original SCI inversion in the Aarhus Workbench

The model that was used for the SCI_Whole_01 (the original) inversion was a 20 layer model with a starting resistivity of 10ohmm, with the first layer boundary at 2m depth and the last one at 300m depth.

The assessment of this original inversion, involving an SCI, was assessed by looking at:

1. The data fit (how well inverted model response fits the measured response),
2. Inverted altitude vs a priori altitude along select lines;
3. Inverted conductivity-depth sections along select flight lines and
4. conductivity-depth slices.

The data fit (Figure 8) shows areas where the modelled data did not fit the measured responses very well. Interestingly, it was noted that many of these areas corresponded with locations where the inverted altitude was very different from the a priori altitude (Figure 9 shows the difference between the input altitude and the inverted altitude). A comparison between Figures 8 and 9 suggest that areas of poor data fit coincide with areas where the attitude derived from inversion and that derived from the altimeter are very different.

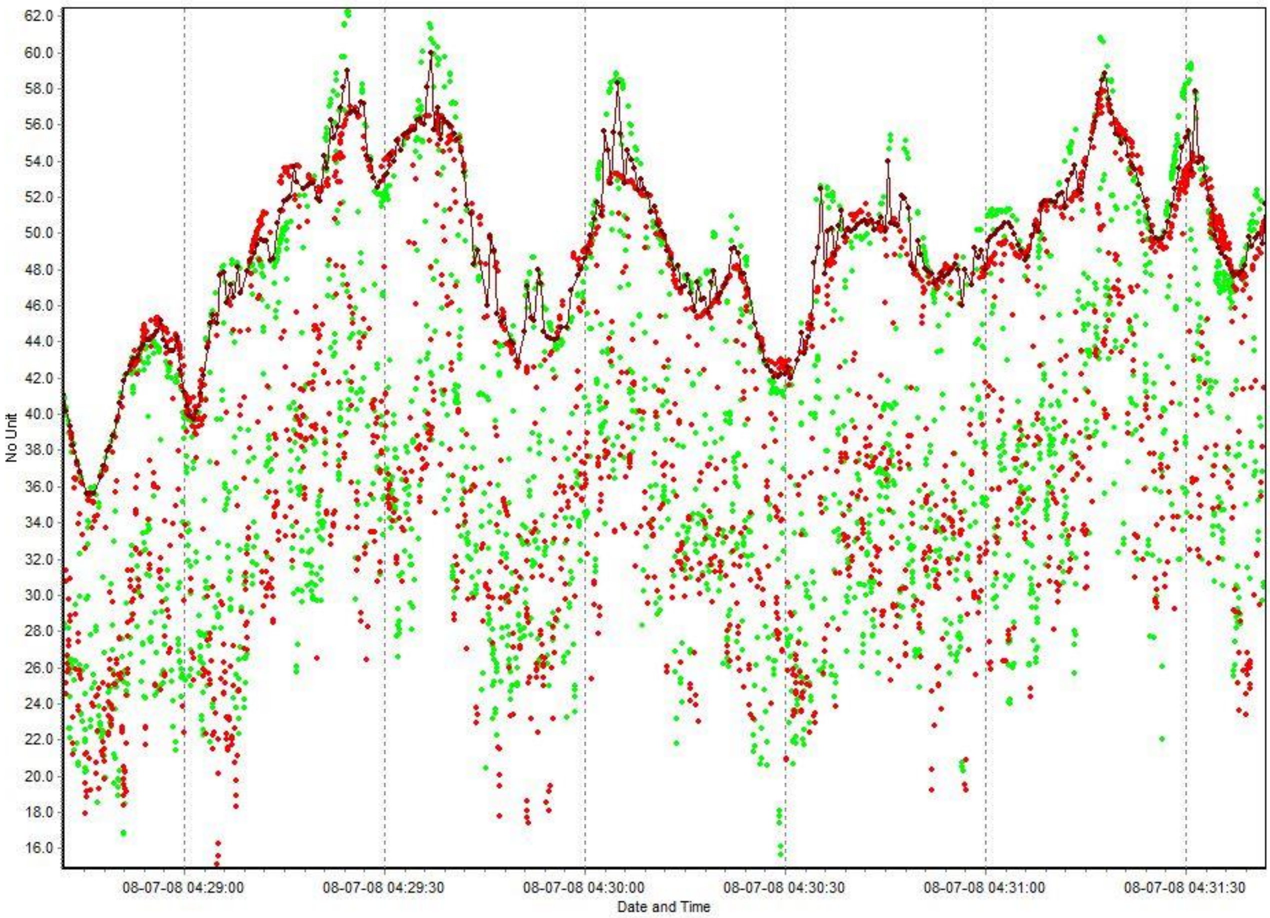

Figure 5: An example of laser altimeter derived altitude data (height of AEM system above the ground) for a flight line of data from the Lake Muir survey. The green and red are the raw altitudes from the two altimeters. The brown line is the processed altitude which is used in the inversion. These averaged data contain a large number of spikes.

To understand why some areas, give a high data fit and/or difference between altitude input and inverted altitude, it is necessary to look at the inverted models in section view. Results from an inversion of line 474400 is shown in Figure 10.

Between 34000 and 36000m along the flight line (on the extreme right of the section) two conductive features are modelled in the data, appearing at an elevation of 130m. At these two points the residual is as high as 8 indicating a poor fit between the model and the data. Analysis of a single sounding at 34500m confirms this (Figure 11). It is also apparent that the difference between the inverted altitude and the input altitude at these points is too high for what is usually acceptable (Figure 10 – enlarged section).

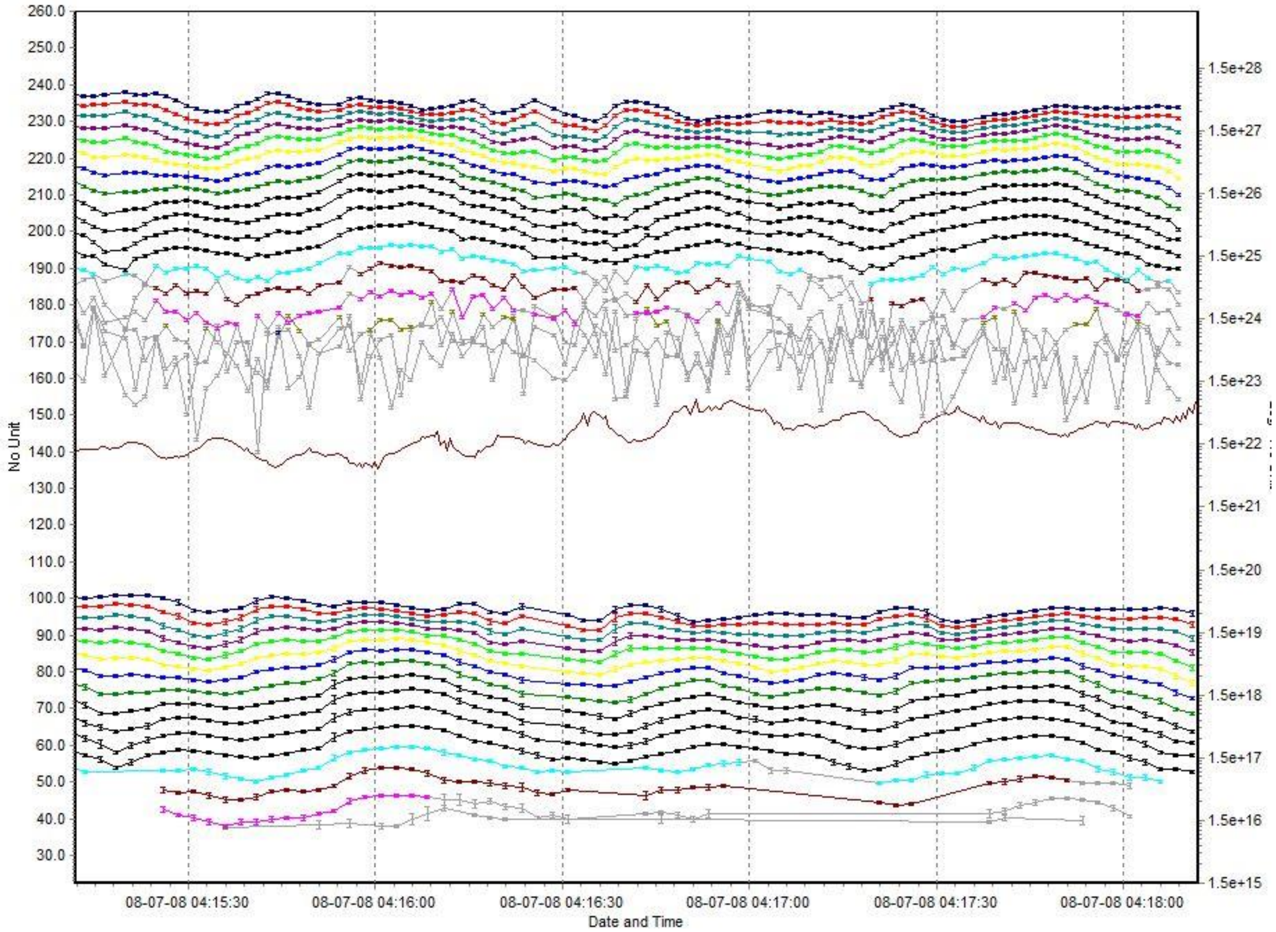

Figure 6: SkyTEM Low Moment gates, with raw amplitude data in the top panel and averaged data at the bottom for one flight line of data acquired at Lake Muir. The filtering process involves the re-sampling of soundings along the flight line, and the removal of noisy (spiky) late time gates.

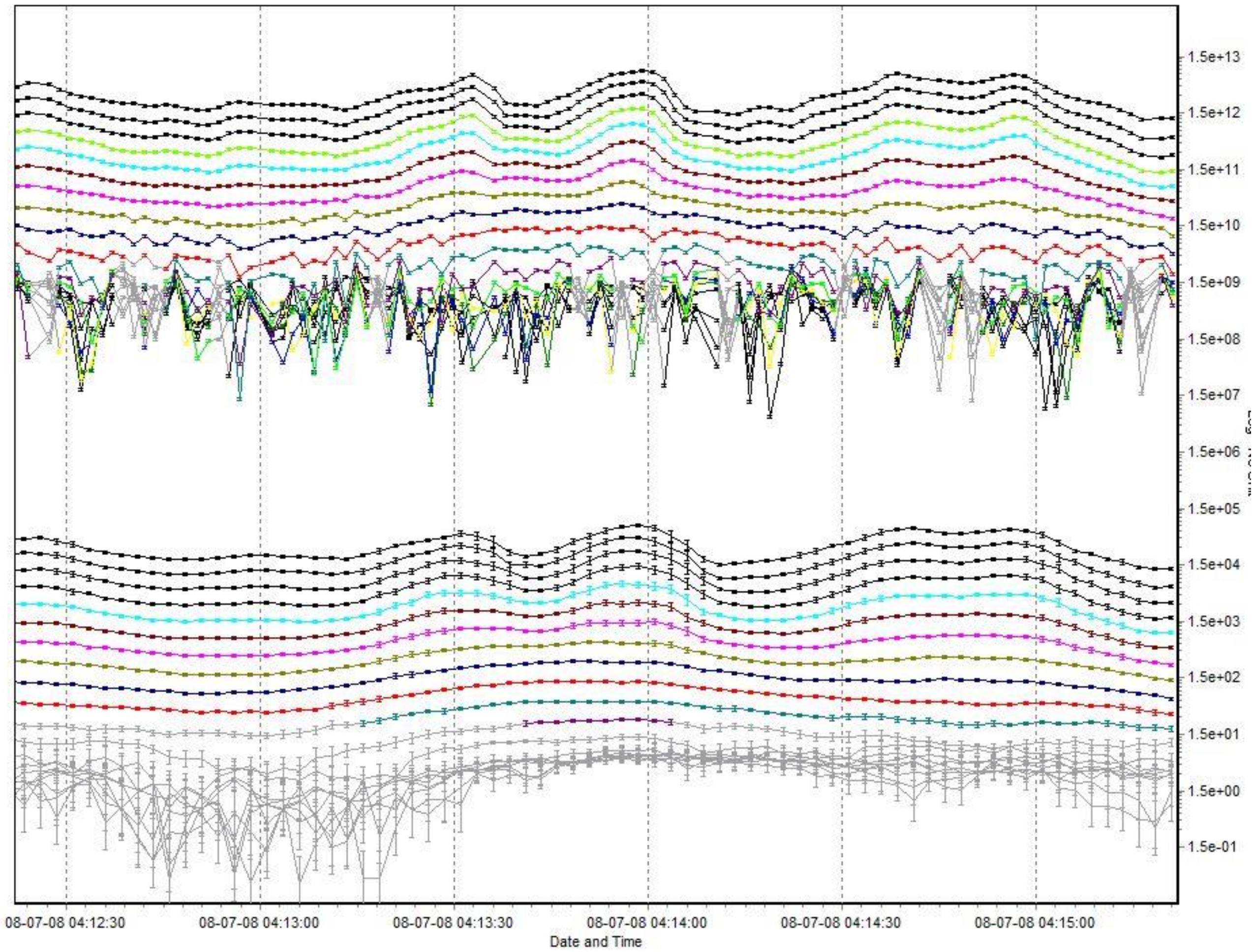

Figure 7: High moment responses, with raw amplitude data in the top panel and averaged data at the bottom for a flightline of data. The averaged data (lower panel) appear to have been excessively smoothed potentially resulting in the smoothing of subsurface conductivity structure at later times (greater depth).

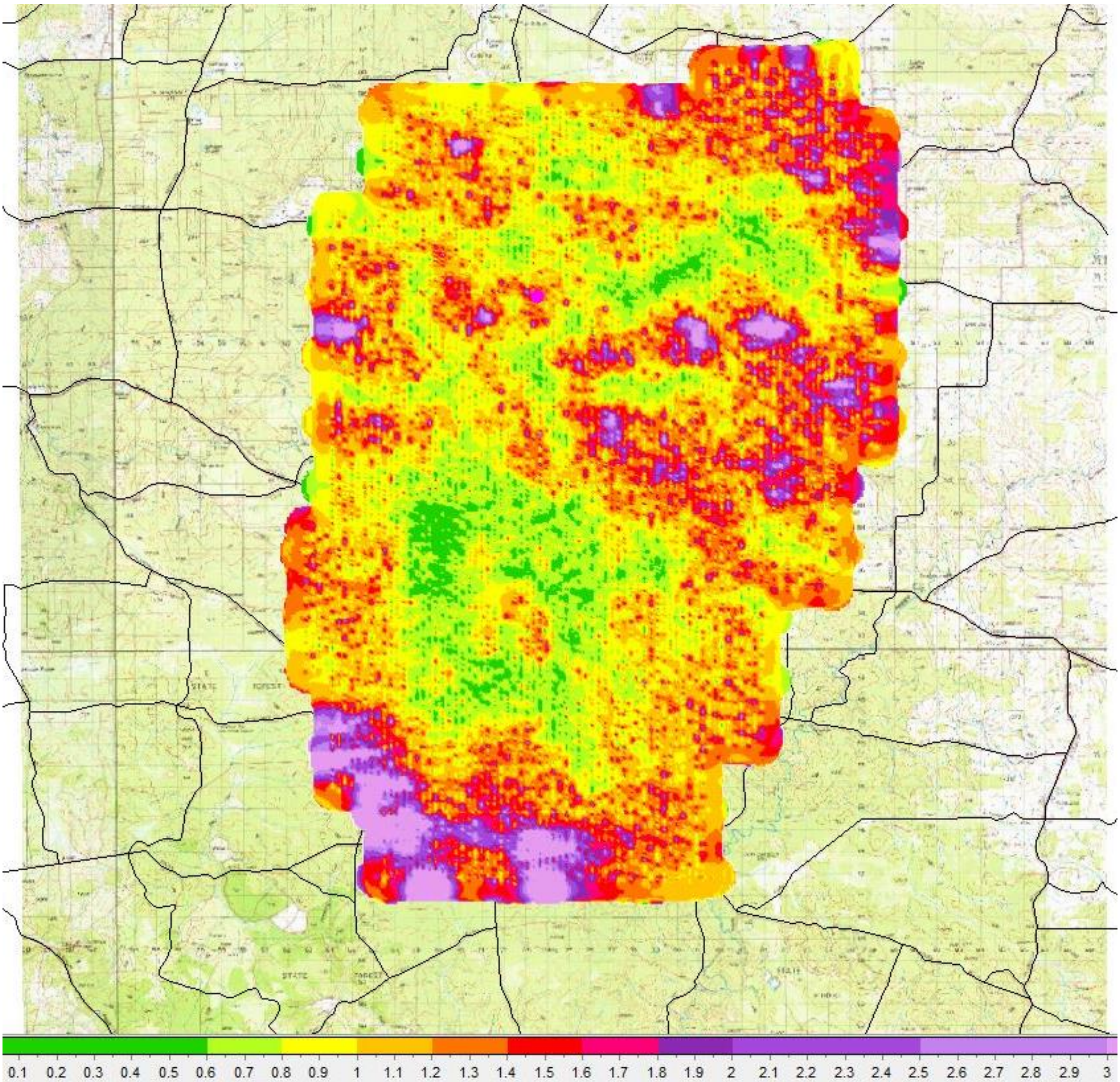

Figure 8: A map of the data fit for the original inversion (SCI_Whole_01) for the Lake Muir survey area. Poor fits correspond to areas coloured as orange, reds and purples.

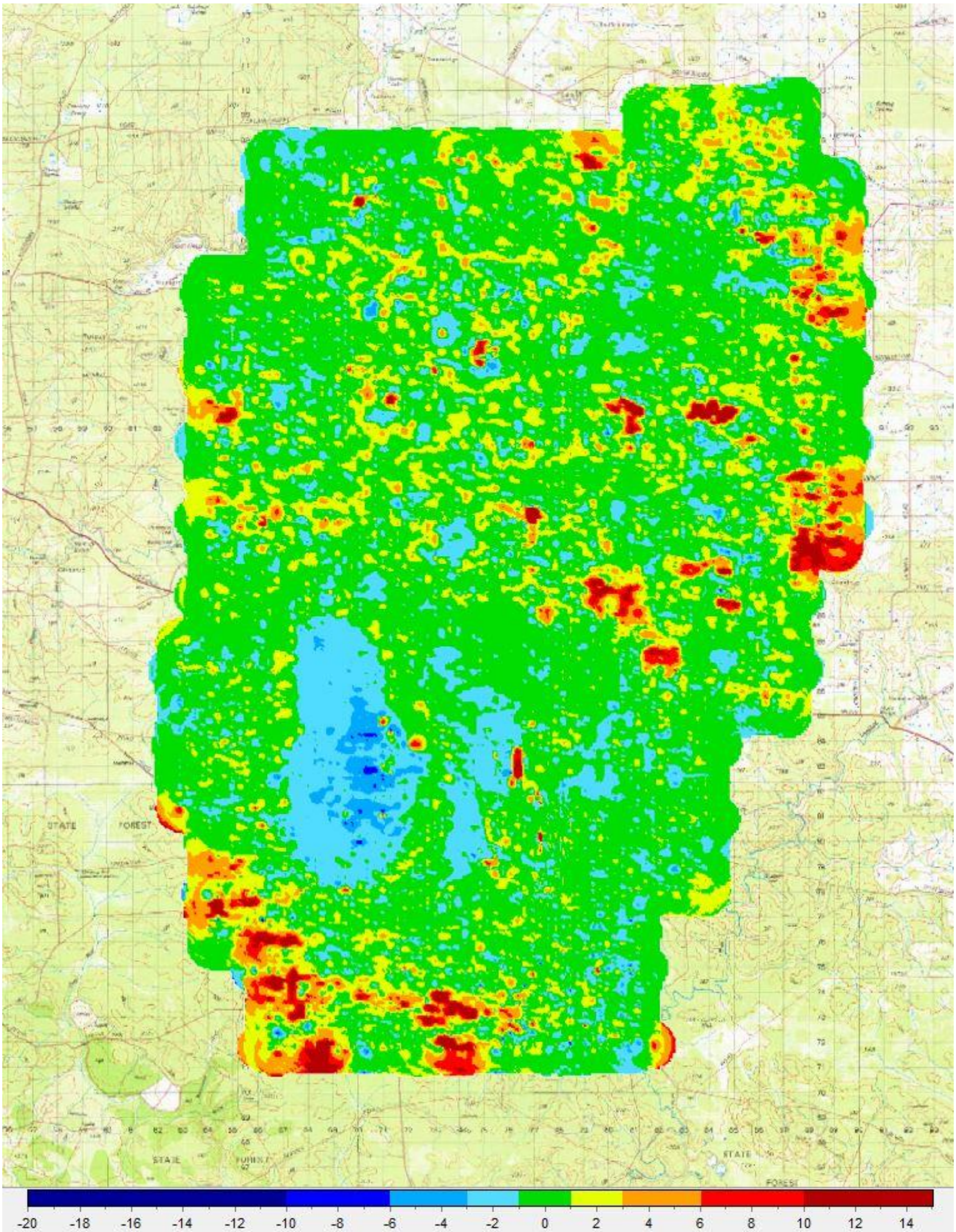

Figure 9: Difference in altitude between the altitude input into inversion and the inverted altitude *from* the inversion.

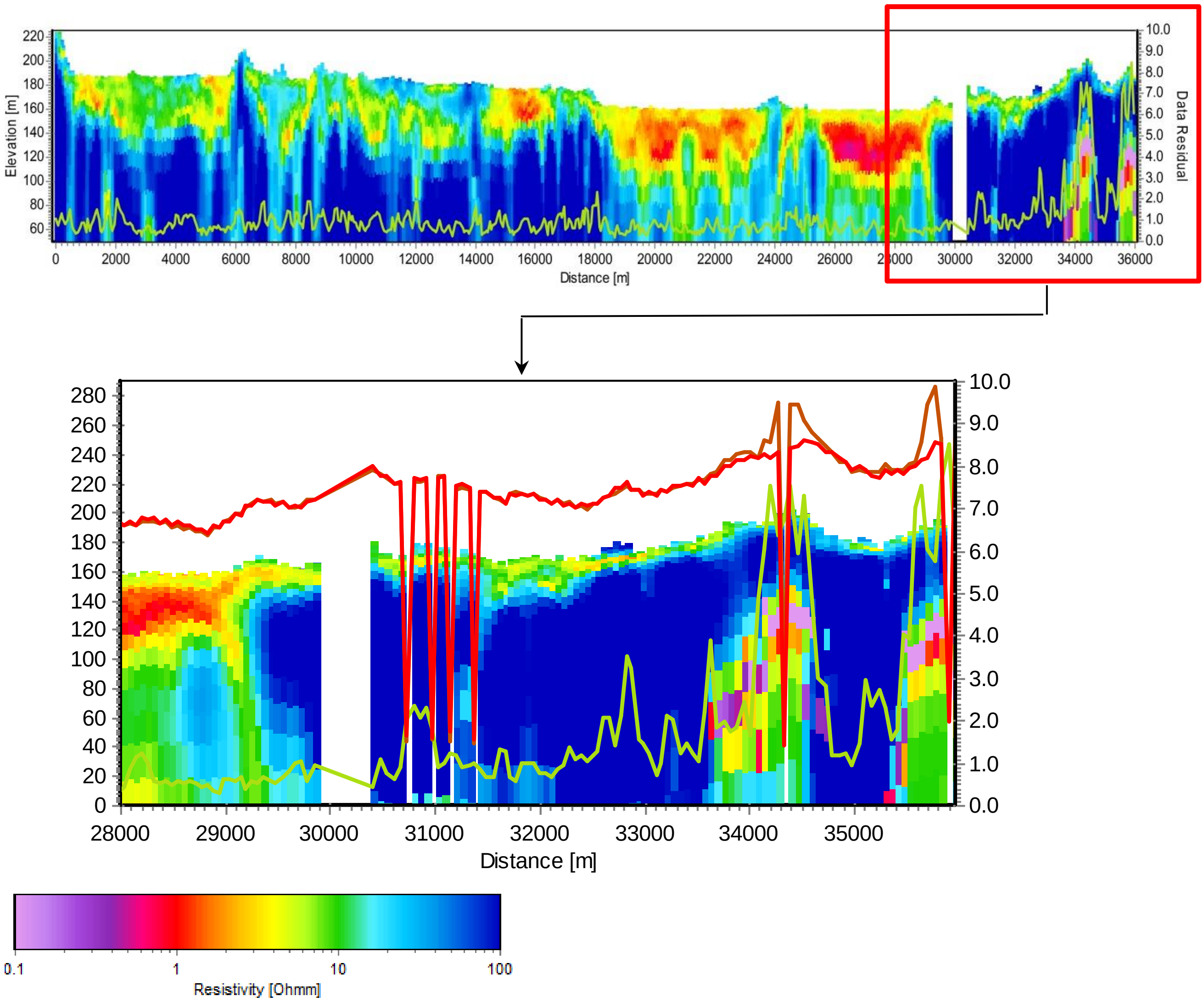

Figure 10: Top panel show SCI resistivity inversion results for Line 474400 from the originally inverted data. Green lines show (in the lower part of the section) the data residual. Bottom panel is an enlarged subset of the right-hand part of the flight line. Poor data fits (and deep conductors) occur where there is a marked difference between the input altitude (red line) and the inverted altitude (brown line). Poor data fits indicated by high data residuals (green line) are also noted to coincide with these discrepancies.

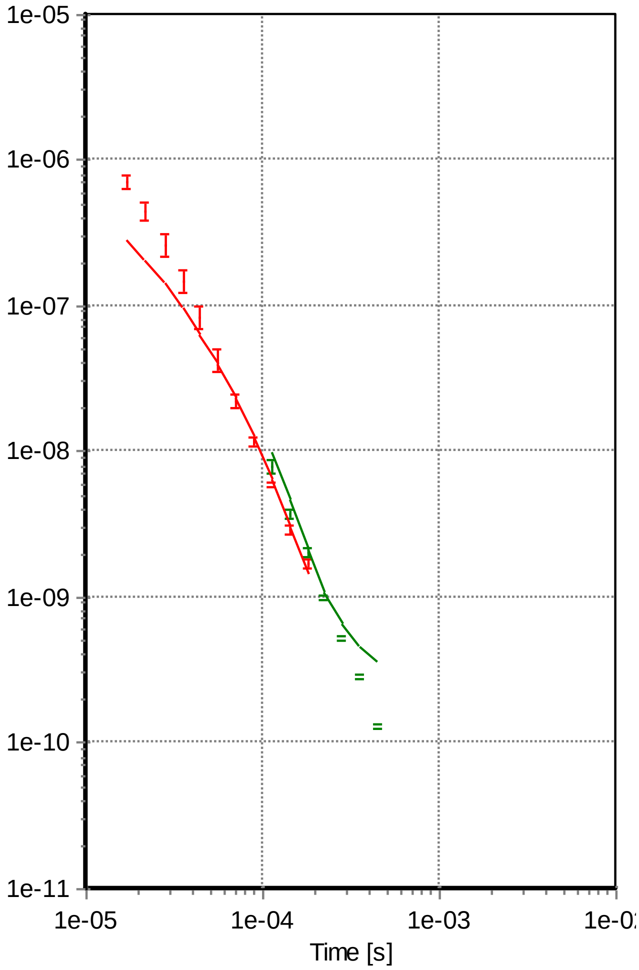

Figure 11: The measured response at a station (or sounding) 34500m along the flight line (see enlarged subset in Figure 10) shown as error bars and the inverted model response shown as the red (low moment) and green (high moment) lines. The data fit for both high and low moments is poor.

2.2 Re-inversion of the data with existing processing

A small subsection of the data consisting of five lines was used as a test area for the reprocessing and inversion of the data. The data were first reinverted without applying any extra or different processing to the data. The starting model for the inversion was changed to a 30 layer model, with first layer boundary at 3 meters and the last one at 350m, and the resistivity was changed to 30ohmm. The main differences between the model from the original inversion (SCI_Whole_01) and the new inversion (Figure 12) are observed in the area around 34-36000m where the data are now better fitted (Figure 13 vs. Figure 11).

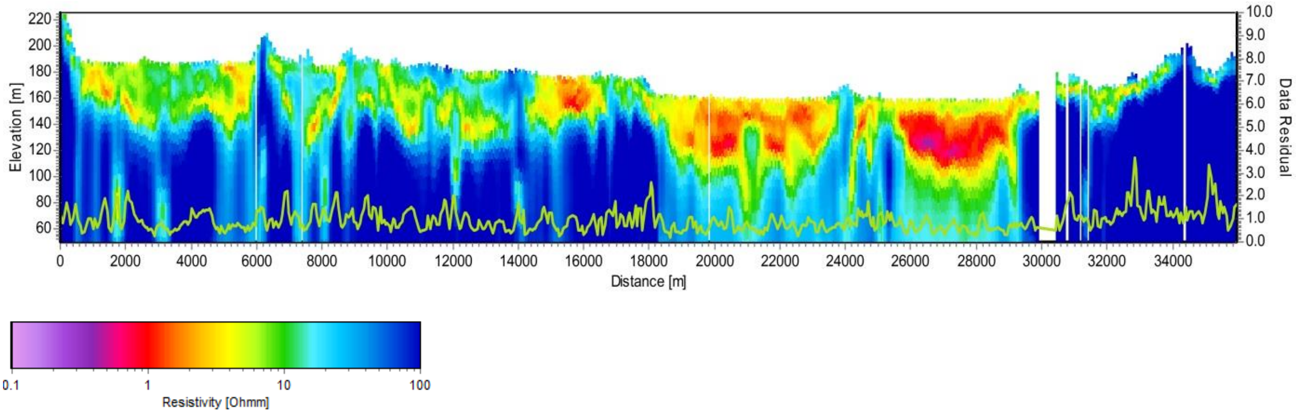

Figure 12: Line 474400 inverted without extra processing. Difference between this inversion and the inversion seen in Figure 10, is exclusively the starting model for the inversion.

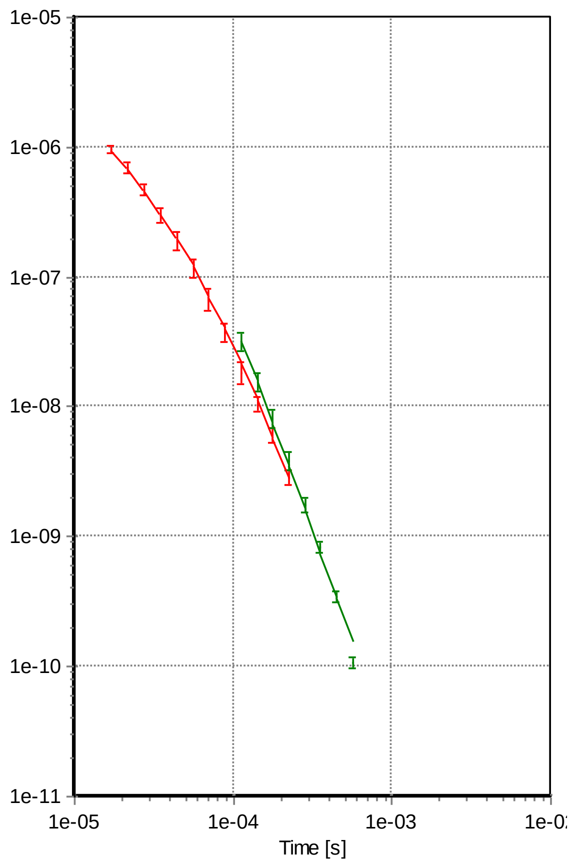

Figure 13: The measured response at a station (or sounding) 34500m along the line plotted in Figure 12 shown as error bars and the inverted model response shown as the line. The data fit for both high and low moments is significantly improved (see Figure 11 for a comparison of the fitting)

2.3 Reprocessing of the raw and averaged data

The data for five lines in the study area were then reprocessed. To produce a more smoothly varying transmitter altitude for these lines, as an input to the inversion, the altitude was reprocessed, and outliers removed. The trapez filter width was also reduced for the high moment to preserve a little more structure in the mid and late time data and kept as it was for the low moment. Features in the data corresponding to the location of powerlines were removed. Late time noise was assessed in the averaged data and manually removed where necessary. The sounding spacing was also changed to 1.7s which seems more in line with the spacing observed in the raw data.

2.4 Inversion with new processing

The reprocessed data were then re-inverted using a starting model with emphasis on the near surface. The first layer boundary was therefore at 0.5m depth and the last layer boundary at 350m depth. The layer thicknesses in between were logarithmically increasing, giving an increase number of thinner layers in the near surface. Figure 14 shows the inverted section for line 474400 with the new processing and the near surface optimised starting model.

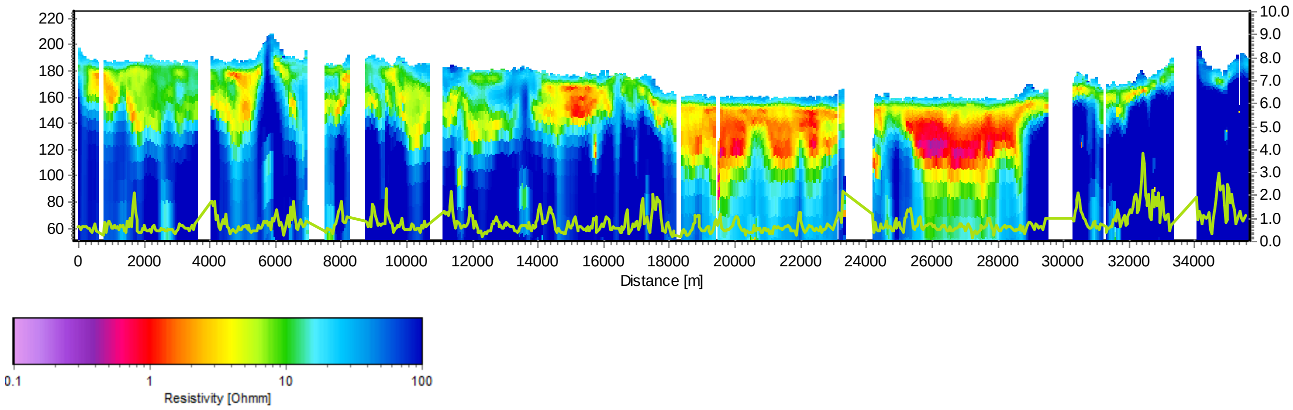

Figure 14: The inversion result for Line 474400 after reprocessing and with an optimised starting model for near surface variability.

2.5 Adding topography (1s SRTM DEM)

An assessment of the topography supplied with the data, which is the measured GPS altitude minus the laser altimeter altitude, revealed that this topography was out by 15-20m, when compared with the 1s DEM. Also comparing collar altitudes of boreholes in the area to the 1s SRTM DEM and the topography generated from the lidar data acquired during the AEM survey showed a better match to the 1s SRTM DEM. The 1s DEM was therefore applied to the data before the inversion. Figure 15 shows the inversion of line 474400 carried out with the near surface optimised starting model, and the 1s DEM applied to the data.

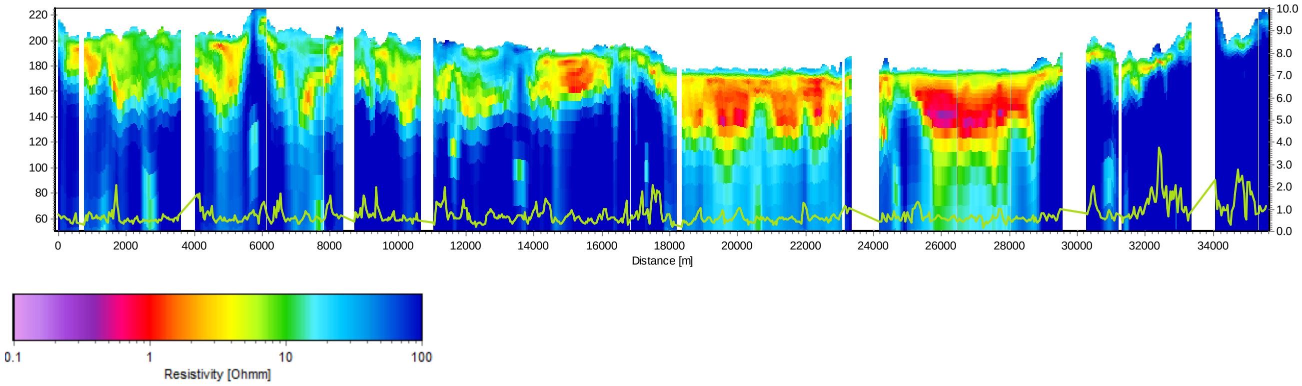

Figure 15: The inversion results for Line 474400 after adding the 1s DEM to the reprocessed data. The same starting model was used that shown in Figure 14.

2.6 Interval conductivities and conductivity depth sections

The following page (Figure 16) shows resistivity-depth sections generated from the inversion of one of the five lines of data that were used to assess the value of reprocessing and re-inversion. The results from revisiting the original processing and inversion are apparent as a smoother more spatially coherent conductivity (resistivity) structure. Consequently, the whole Lake Muir data set was subject to the same approach and re-inverted. Thirty conductivity-depth intervals or interval conductivities were generated in 1m intervals from the surface to 10 metres, 2m intervals between 10 and 20m, 5m intervals to 70m, and then 10m intervals to 120m (see, for example, Figure 17).

Displaying inversion results as conductivity-depth images is a common way to visualise the spatial distribution of the conductivity within a survey area. In areas with large topographical variations it can be beneficial to display conductivities not only with depth but also as elevation intervals, accounting for variations caused by the topography. Elevation intervals were also generated.

The interval conductivities show spatially varying conductivity structure across the study area.

Conductivity-depth sections have also been generated for each flight line. These have the Depth of Investigation (DoI) appended to assist interpretation. More detail on the definition of a DoI is given in the next section. An example of one of these sections is presented in Figure 18.

2.7 Depth of investigation (DoI)

The presentation of conductivity models derived from AEM systems can be misleading if there is no attempt made to qualify the depth of investigation (DoI) of the measurement system. The depth of investigation is a complex quantity, being a function of the power, sensitivity and accuracy of the acquisition system, environmental noise levels (e.g. sferic and powerline sources), geologic complexity, the host conductivity and the target characteristics (e.g. a discrete object or an extensive layer, conductivity contrast to the surrounds) and the inversion procedure used (Christiansen and Auken 2012). To ensure that the observed variations in measured conductivity reflect changing ground conditions, rather than inversion or model dependent changes arising from the inversion process, an estimate of the depth of investigation is calculated and presented on the conductivity-depth sections. This information assists the interpreter, helping to quickly evaluate the results and their validity. The DoI provides a depth to which the model is the most reliable, and model information below the DoI should be used with caution.

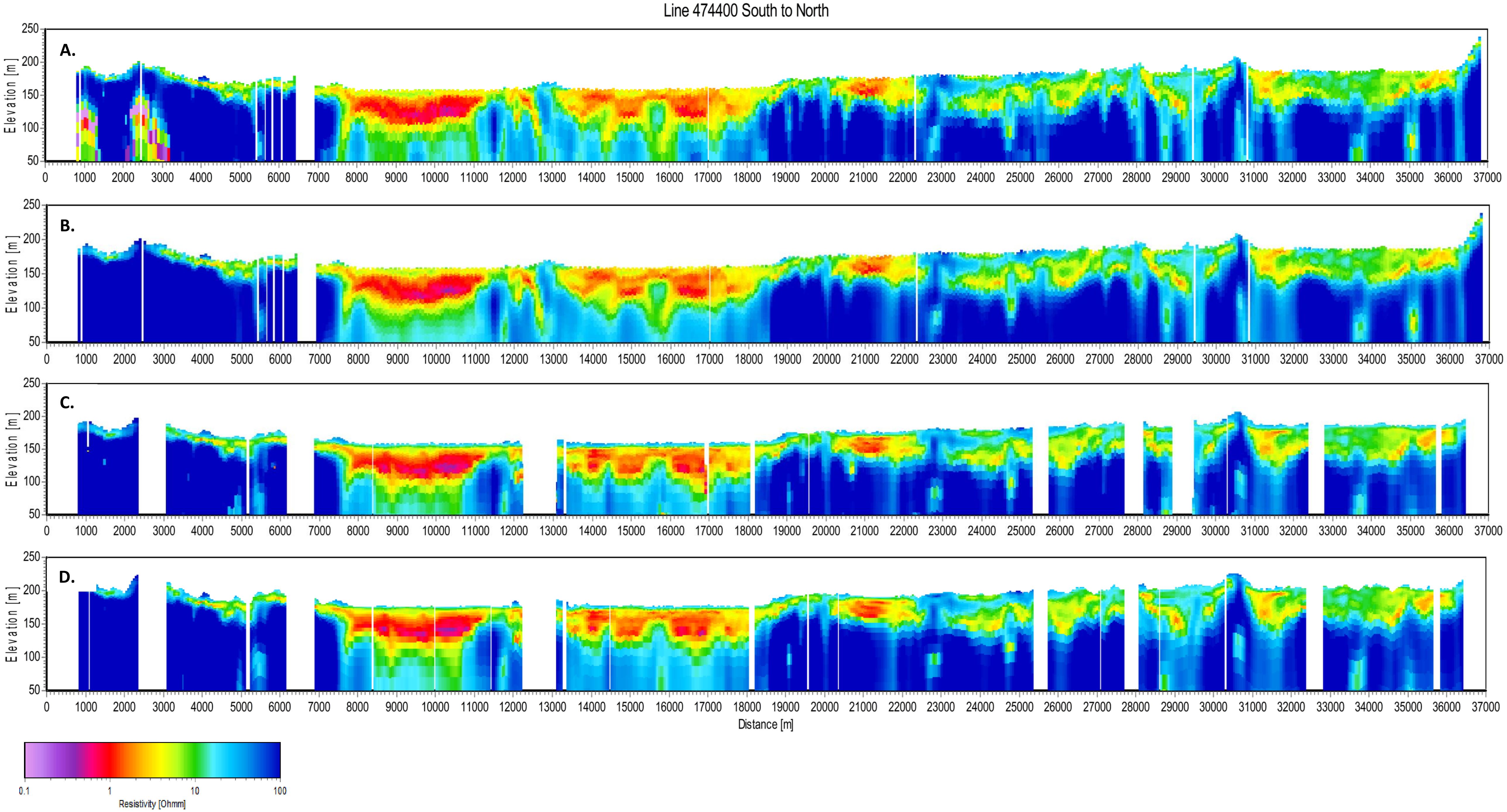

Figure 16: Resistivity-depth sections for line 474400. The original inversion in Aarhus Workbench with a starting model of 10 ohmm is shown in panel A. Panel B. is the result from re-inverting the originally processed data with a starting model of 30 ohmm. Panel C. is the result from reprocessing and then re-inverting the data for thinner near surface layers but also with a starting model of 30ohmm. Panel D. is the result from adding the 1sec SRTM DEM to the data and then inverting with the same parameters as used in Panel C. The revised starting model improved data fit. Parts of the section missing data (presented as gaps) are where they were removed as part of the processing step to eliminate noise from cultural or other features (e.g. powerlines etc)

The DoI determination used here is based on the cumulative sensitivity of the actual model output from the inversion (it includes the full system response and geometry) and is described in Christiansen and Auken (2012). The data noise and the number of data points are integrated into the calculation, which is based on the final inversion model output and a recalculated sensitivity (Jacobian) matrix. In general terms the more conductive the ground, the ability to resolve deeper variations in conductivity (or the depth to which the inverted model is reliable) decreases. In more resistive ground, the system can resolve those variations more reliably to greater depths. The modelled conductivities in the Lake Muir survey varies from conductive over the lakes resulting in a shallower DoI, to more resistive areas in higher parts of the landscape. In these areas the DoI is much deeper (Figure 18).

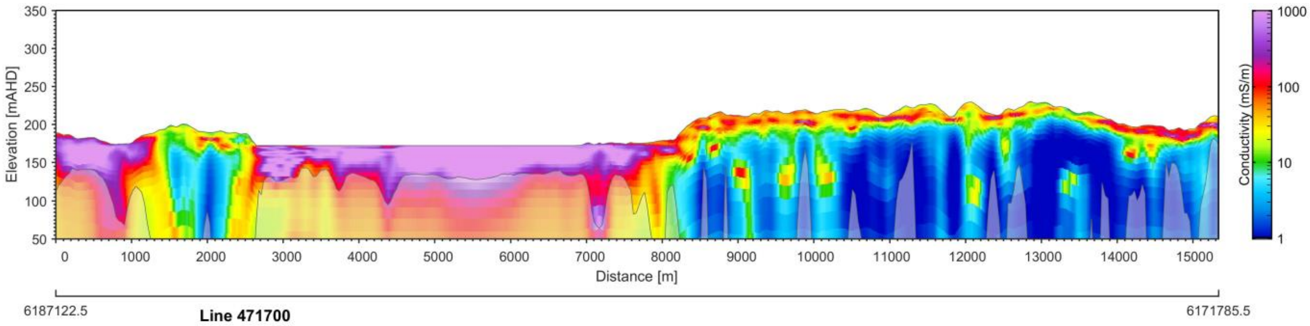

Figure 17: Conductivity-depth section for Line 471700. A grey line, with a partially transparent shading beneath indicates the Depth of Investigation (DoI) in the section. Where conductivities are higher in the near surface the DoI is shallower. Where the landscape is resistive, the DoI is much deeper, and in some instances plots below the depth extent of the section.

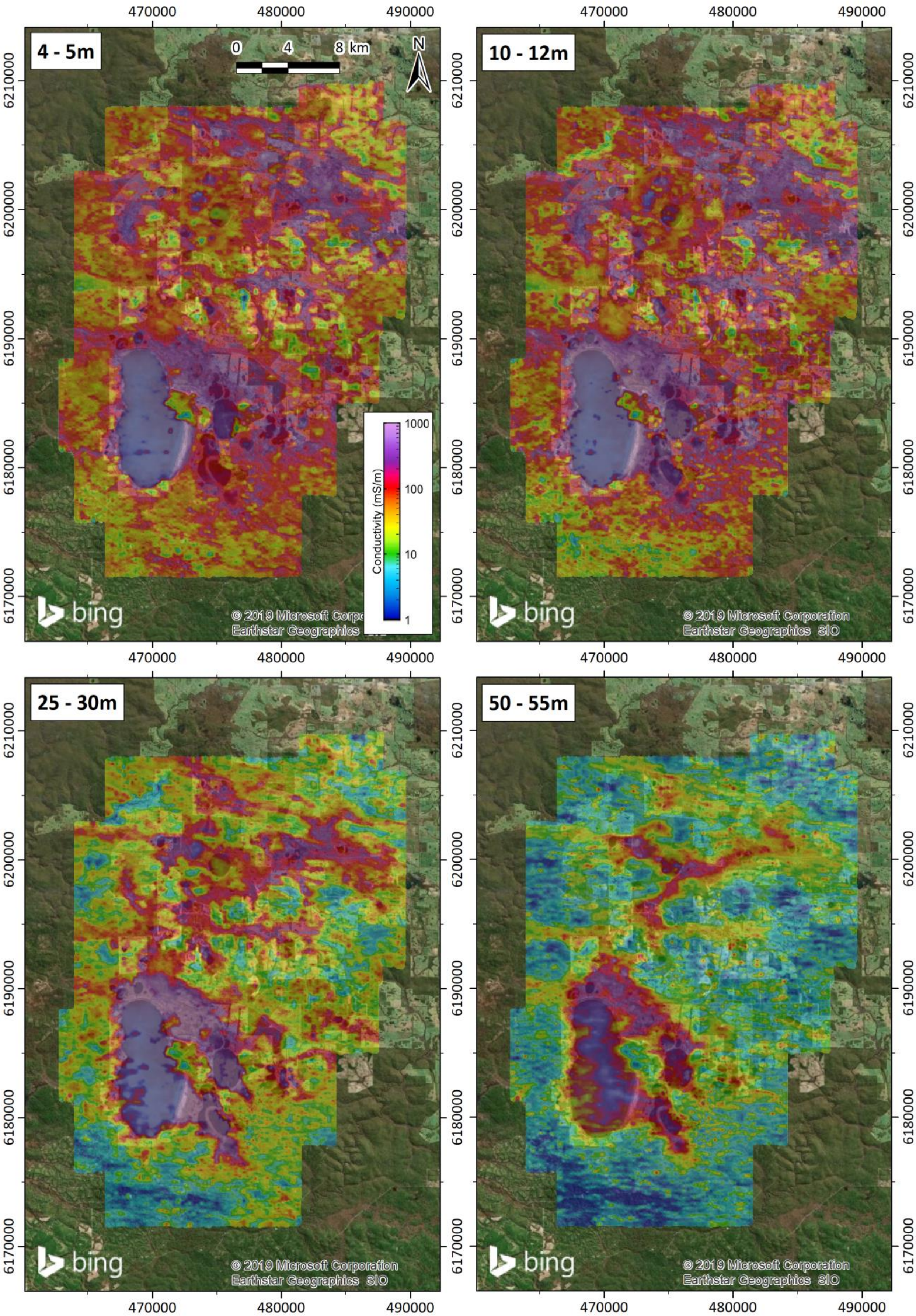

Figure 18: Example interval-conductivities generated for the Lake Muir SkyTEM survey.

3 Summary

A review of an original attempt to process and invert SkyTEM data over Lake Muir in Western Australia, identified several shortcomings in the results, including the presence of artefacts in the inversions, and a problem with the topographic surface used to fit the data. In light of these issues, the data set was reprocessed and re-inverted. Emphasis was also given to emphasising variability in the conductive structure in the near surface. A set of conductivity sections, detailing the depth of investigation, and conductivity-depth intervals were generated.

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