INVERSION OF TEMPEST AEM SURVEY DATA
HONEYSUCCLE CREEK, VICTORIA

Ross C Brodie and Adrian Fisher

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Executive summary

This report describes the geophysical inversion of the Honeysuckle Creek TEMPEST airborne electromagnetic (AEM) survey data to produce subsurface electrical conductivity predictions using a layered earth inversion algorithm developed by Geoscience Australia (GA-LEI). The GA-LEI algorithm has significantly improved on previous conductivity predictions generated by inversion and conductivity depth transform methods, as shown by comparisons between conductivity predictions and ground truth data (measurements of conductivity acquired down boreholes). Correlation between the GA-LEI predictions and borehole measured conductivities ($R^2 = 0.77$) is better than for previous predictions from inversions ($R^2 = 0.05$ and $0.47$), and conductivity depth transforms ($R^2 = 0.04$ and $0.47$).

This improvement is attributed to the GA-LEI methodology, which solves for three unmeasured components of the system geometry as well as the ground conductivity model, and is guided by downhole conductivity and geological knowledge. In addition, this inversion of the Honeysuckle Creek data used both the X and Z components of the measured response, and uses minimally processed data which have fewer introduced assumptions than data previously used. Being an inversion, it compares the calculated response from the subsurface conductivity predictions with the measured response data, ensuring the conductivity predictions results are consistent with measured data – something not done with previous transform methods.
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1 Introduction

This report describes the geophysical inversion of airborne electromagnetic (AEM) survey data to produce subsurface electrical conductivity predictions. The AEM data were acquired by Fugro Airborne Surveys (FAS) during 2001 with the TEMPEST system. The Honeysuckle Creek survey area is located to the southeast of Shepparton in Victoria, Australia (Figure 1). The survey was funded by the Murray Darling Basin Commission under its Strategic Investigations and Education (SI&E) Program, as part of Airborne Geophysics - SI&E Project D2018. The project was a pilot testing the relevance of airborne geophysics data for salinity management, and evolved from the National Geophysics Project originally sponsored under the National Dryland Salinity Program. The survey was project managed by the Bureau of Rural Sciences (BRS) with supervision and geophysical advice provided by Geoscience Australia (GA).

![Figure 1](image.png)

**Figure 1** Location of the Honeysuckle Creek AEM survey area. The map boundary is also the boundary of the 3D geological map, and the red line is the boundary of the AEM survey. Outcropping basement rocks that also correspond to areas of higher relief are shown as dark grey.
After the initial data acquisition and processing, and before any ground follow up was carried out, three sets of conductivity predictions were generated by FAS. These predictions were generated by conductivity depth transforms (CDT) using the software EmFlow (Macnae et al., 1998) and two versions of three-layer layered earth inversions (LEI) using an algorithm described by Sattel (1998). The acquisition of downhole conductivity logs later in 2001 revealed that the original CDT tended to predict a greater amount of high conductivity material close to the surface than the downhole conductivity logs measured. Having access to the downhole conductivity logs Christensen (2002, 2004) generated a forth set of ‘calibrated’ conductivity predictions using EmFlow. This calibration was performed by adjusting the transmitter height parameter in EmFlow used to compute the CDT data, rather than by any changes to the methodology or observed data itself. These predictions showed improved agreement with known salinity occurrences and (hydro) geology.

During 2003 GA developed a layered earth inversion algorithm which, when applied to TEMPEST data, significantly improved existing CDT conductivity predictions on a similar dataset (Lane et al., 2004a; Lane et al., 2004b). Herein we refer to this algorithm as the GA-LEI. In 2006 BRS contracted GA to investigate if similar improvements could be made on the Honeysuckle Creek dataset in a study (Phase I) that performed GA-LEI inversions on airborne samples nearest to the available downhole conductivity logs and compared the predictions with the earlier generations. The Phase I study concluded that the GA-LEI algorithm would be able to provide better conductivity estimates (Reid and Brodie, 2006). The present report is concerned with the application of the GA-LEI methodology, guided by both downhole conductivity and geological knowledge, to the complete dataset in order to generate new conductivity predictions and derived products (Phase II).

The present report is concerned with the application of the GA-LEI methodology, guided by both downhole conductivity and geological knowledge, to the complete dataset in order to generate new conductivity predictions and derived products (Phase II).

Section 2 provides background information on the development of the GA-LEI algorithm. A full description is supplied in Appendix A for those readers interested in the technical details. Specific non-technical information relating to its application to the Honeysuckle Creek TEMPEST AEM dataset is detailed in Section 5.

2 Background to Geoscience Australia Layered Earth Inversions

As a towed-bird fixed-wing AEM system such as TEMPEST moves along a survey flight line its transmitter (TX) loop and receiver (RX) coils continuously change height and orientation with respect to the ground as well as with respect to each other. The overall geometrical arrangement is known as the system geometry. For TEMPEST, the height of the TX above the ground is dynamically measured with a radar and/or laser altimeter. The TX loop orientation, defined by its pitch and roll angle, is dynamically measured via gyroscopes. However to date it has been operationally impossible to dynamically measure the relative position and orientation of the RX coils (receiver geometry), for example with laser range finders or GPS technology (Smith, 2001b). The system geometry is an inherent input into the estimation of a conductivity distribution from AEM data, whether this estimation is by a CDT or LEI algorithm. However since the receiver geometry is not measured, it must be either assumed or estimated for use in CDT and LEI algorithms.

TEMPEST data are recorded as a stream of digital samples spaced 13.33 μs (75,000 Hz) apart during both the on-time TX loop current pulses and the off-time. This full waveform recording allows sophisticated digital signal processing techniques to be applied to the data. Thus, as a function of time across the full waveform, the system measures and records the total field response.
at the RX which is a summation of the primary field response that originates directly from currents in the TX loop and the secondary field (or ground response) that originates from eddy currents induced in the ground. The primary field is dependent on the system geometry, whereas the secondary field is a function of both the system geometry and the ground conductivity. Hence it is the secondary field that is diagnostic of the subsurface conductivity. If the system geometry was known the primary field could be calculated from first principles and subtracted from the total field to leave the diagnostic secondary field. However, since in reality there is no independent knowledge of the primary field, the secondary field or the system geometry, none of the three quantities can be directly isolated.

To resolve this impasse, in TEMPEST data processing an attempt is made to decompose the measured total field into primary and secondary components using the knowledge that the secondary field theoretically should approach zero as frequency approaches zero (or as delay time approaches infinity). This decomposition estimates the primary field such that the time domain in-phase component (Smith, 2001a) of the remaining ground response, consisting of sums of exponential basis functions, is minimised (Lane et al., 2004a). Minimising the time domain in-phase component of the ground response is akin to assuming a low conductivity ground model particularly at depth. Once the primary field is estimated, it is then possible to estimate the relative position of the RX coils, assuming that the bird was flying straight and level (i.e. RX in-line with the TX and with zero roll, pitch and yaw).

The assumptions of low ground conductivity and that the RX coils were flying straight and level are thus inherent in the processed data and estimated receiver position before they are input into CDT or LEI algorithms. If these assumptions are not good, the consequence is that conductivity estimates derived from the CDT or LEI algorithms are biased toward ground models with low conductivity at depth and the true conductivity is underestimated at depth. There is a related tendency to compensate for the lack of total conductance, needed to satisfy the data, by overestimating the true conductivity in the near surface. This was observed by (Lane et al., 2004b) and has been observed for the Honeysuckle Creek dataset (Christensen, 2002, 2004; Reid and Brodie, 2006) when estimates were compared to ground truth data. A further repercussion is that the fitting procedure may not be able to find any layered conductivity structure that is consistent with both the X and Z component data. In this case the CDT or LEI can be run on the X and Z component data separately; however the resulting conductivity models will be different.

The recognition of these limitations led to the work described by Lane et al. (2004a), and has since developed into the GA-LEI algorithm. The rationale behind the algorithm is that since the primary field, secondary field, receiver geometry and ground conductivity cannot be independently isolated, they should at least be treated as components within a single unifying framework. To achieve this, the usual sequentially applied steps of: separating the primary and secondary fields; estimation of receiver geometry; estimation of ground conductivity; and comparison to ground truth information are carried out in one inversion procedure that guarantees (or at least maximises) mutual consistency between each of the items. The measured components of the system geometry and the observed total field data are input into the inversion algorithm, along with a reference model compiled from available ground truth information. The algorithm solves for the unmeasured components of the system geometry and the ground conductivity model. Separation of the primary and secondary fields is unnecessary but can be an incidental output from the procedure.
3 Data acquisition and processing

The AEM data were acquired by Fugro Airborne Surveys (FAS) in May and June 2001, using the TEMPEST system described by Lane et al. (2000). Details of the survey operations are provided in Lawrence et al. (2001). The survey acquisition parameters are summarised in Table 1.

<table>
<thead>
<tr>
<th>Aircraft:</th>
<th>CASA C212-200 Turbo Prop, VH-TEM</th>
</tr>
</thead>
<tbody>
<tr>
<td>Date:</td>
<td>4 May to 18 June 2001</td>
</tr>
<tr>
<td>Flight line spacing:</td>
<td>200 metres</td>
</tr>
<tr>
<td>Flight line direction:</td>
<td>east-west</td>
</tr>
<tr>
<td>Line kilometres:</td>
<td>6,082 kilometres</td>
</tr>
<tr>
<td>Nominal flying height:</td>
<td>115 metres above ground level</td>
</tr>
<tr>
<td>Along line sampling:</td>
<td>0.2 seconds (~12 metres) stacked and processed AEM</td>
</tr>
</tbody>
</table>

The initial data processing was also carried out by FAS in 2001. For full details on the processing see Lawrence et al., (2001). For convenience the steps involved in TEMPEST data processing are summarised below from Lane et al. (2004b).

i. Sferic filtering via wavelet transforms.
ii. Stacking with a three-second wide cosine-tapered stacking filter. Output from the stacking filter was drawn at 0.2-second intervals.
iii. Filtering to reject VLF and low frequency noises sources.
iv. Deconvolution of the system transfer function and normalisation for the receiver coil effective area, transmitter loop current, transmitter loop turns and transmitter loop area.
v. Convolution of the resultant impulse response with a square waveform.
vi. Windowing to times shown in Table 2.
vii. Primary field estimation and removal.
viii. Geometry estimation.
ix. Height, pitch, roll and geometry correction (not used in the GA-LEI process).
Table 2  Window times and estimated noise levels

<table>
<thead>
<tr>
<th>Window</th>
<th>Window times (seconds)</th>
<th>*Estimated additive noise (fT)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Start time</td>
<td>End time</td>
</tr>
<tr>
<td>1</td>
<td>0.0000066667</td>
<td>0.0000200000</td>
</tr>
<tr>
<td>2</td>
<td>0.0000333333</td>
<td>0.0000466667</td>
</tr>
<tr>
<td>3</td>
<td>0.0000600000</td>
<td>0.0000733333</td>
</tr>
<tr>
<td>4</td>
<td>0.0000866667</td>
<td>0.0012666667</td>
</tr>
<tr>
<td>5</td>
<td>0.0001400000</td>
<td>0.0002066667</td>
</tr>
<tr>
<td>6</td>
<td>0.0002200000</td>
<td>0.0003400000</td>
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<td>7</td>
<td>0.0003533333</td>
<td>0.0005533333</td>
</tr>
<tr>
<td>8</td>
<td>0.0005666667</td>
<td>0.0008733333</td>
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<tr>
<td>9</td>
<td>0.0008866667</td>
<td>0.0013533333</td>
</tr>
<tr>
<td>10</td>
<td>0.0013666667</td>
<td>0.0021000000</td>
</tr>
<tr>
<td>11</td>
<td>0.0021133333</td>
<td>0.0032733333</td>
</tr>
<tr>
<td>12</td>
<td>0.0032866667</td>
<td>0.0051133333</td>
</tr>
<tr>
<td>13</td>
<td>0.0051266667</td>
<td>0.0079933333</td>
</tr>
<tr>
<td>14</td>
<td>0.0080066667</td>
<td>0.0123933333</td>
</tr>
<tr>
<td>15</td>
<td>0.0124066667</td>
<td>0.0199933333</td>
</tr>
</tbody>
</table>

*Estimated multiplicative noise
1.4%  1.3%

*See Section 5.2 for an explanation of the noise estimates.

4  Prior information

4.1  Downhole logs

Twelve downhole conductivity logs were acquired by BRS in the Honeysuckle Creek AEM survey area in conjunction with an air core drilling program in 2002 (Dent, 2003). An estimate of the average conductivity profile, as a function of depth, was calculated by averaging the downhole logs over one metre intervals. The average profile and the number of downhole logs included in the average are shown in Figure 2. The figure also shows a piecewise approximation of the average profile that was used to construct a reference model in the preliminary inversion run (Section 0).
4.2 Stratigraphic information

Stratigraphic information on the subsurface of the Honeysuckle Creek AEM survey area was examined to provide some geological context for the inversion process, mainly to assist in establishing a starting model for the preliminary inversion run (Section 5.5). It was also used to assist with the interpretation of the inversion results, such as the production of a depth to basement surface (Section 6.5). The following section describes the sources of stratigraphic information, their interpretation and a summary of the production of a 3-dimensional surface using 3D GeoModeller software.

Stratigraphic information was obtained from geology maps and borehole lithological descriptions. The 1:1 000 000 digital surface geology map by Raymond et al. (2007) was the main map used, which was based on the work of Edwards and Slater (2001) and Vandenberg (1997). The solid geology map of Victoria by Vandenberg et al., (2000) was also used to guide the interpretation of boreholes under sedimentary cover. Lithological descriptions from boreholes were collected from three sources: the Bureau of Rural Sciences (Dent, 2003), CSIRO Land and Water (English et al., 2004), and Geoscience Victoria (Geoscience Victoria, 2006).

The borehole lithological descriptions were interpreted into three simplified stratigraphic classes: sediments, saprolite and basement. Sediments included the unconsolidated clays, sands and gravels of the Cainozoic Murray Basin and Quaternary deposits, while basement included all the Palaeozoic rocks of the Lachlan Fold Belt (mainly folded and faulted sandstones and siltstones of the Jordan River and Walhalla Groups of Maher et al. (1997)) and the Violet Town Volcanics (quartz-rich...
ignimbrites). Saprolite (*in situ* weathered basement) was only differentiated in the BRS and CSIRO boreholes. Each borehole was also assigned a reliability value based on who had conducted the lithological logging. It was assumed that logs recorded by a regolith geoscientist would be the most reliable (a); logs recorded by a geologist would be slightly less reliable (b) as they would not have had as much training in identifying regolith materials; boreholes logged by a driller are considered less reliable still (c); while the least reliable boreholes were those where a basement lithology contradicted the geology maps (d). These reliability values were taken into account when the stratigraphic information was used to calibrate the automated depth to basement conductivity threshold value (Figure 11).

The interpreted borehole stratigraphic boundaries (base of sediments) were used as input data in the construction of a 3D surface using the 3D GeoModeller software. The boreholes did not provide enough information regarding saprolite thickness, and so only the sediment thickness was modelled. To give the 3D surface some regional context, it was decided to interpret boreholes from an area larger than the AEM survey (Figure 1). This area contained 421 interpreted boreholes, though some did not penetrate to the base of the sediments and could only be used as markers of minimum sediment thickness. Other input data that were used in the construction of the surface were: the SRTM Version 2 90 m DEM, resampled to a 250 m grid; nodes from the boundaries of outcropping basement rocks, that were simplified and modified to better conform to the DEM; and, some user defined foliation control points that were used to control the orientation of the modelled surface adjacent to steep hills. The 3D GeoModeller program created a surface of best fit through the various control points including the borehole base of sediment control points, the outcropping basement rock boundary control points, and control points generated from the DEM that forced the base of sediments surface to dip away from areas of outcropping basement. The resulting surface was then masked by the outcropping basement rock polygons, and exported as an ERMapper raster dataset with a 250 m grid cell size (Figure 3).
Figure 3 The surface representing the depth to the base of the sediments constructed with the 3D GeoModeller software from mapped outcrop and borehole stratigraphic information but without any AEM data inversions. White areas on the image represent zero depth (outcropping basement).
5 Inversion

5.1 Data

The data input into the inversion algorithm were not the FAS height pitch roll and geometry corrected data that are usually supplied by FAS. It is necessary to input the non-geometry corrected data because the inversion algorithm uses the measured elements of the system geometry and re-estimates three of the non-measured elements of the system geometry.

The processed non-geometry corrected data delivered by FAS represent the estimated secondary field (ground response). They are in fact, the measured total field data minus the estimated primary field. The actual primary field data are not supplied by FAS. Since the inversion algorithm makes use of total field data we had to reconstruct the total field by first recalculating the estimated primary field from (measured, assumed and estimated elements of) the system geometry using dipole formulae (Wait, 1982; Lane et al. 2004b); and then adding the result to the secondary field data (see Appendix A, Section A.2.6). In making the primary field calculation we were consistent with the (reverse) calculation made by FAS processing when estimating the system geometry from the estimated primary field. Specifically that means we: used the gyroscope measured transmitter pitch and roll; assumed the receiver coil assembly’s roll, pitch and yaw was zero; assumed the transmitter to receiver horizontal transverse separation was zero; and used the FAS estimated transmitter to receiver horizontal in-line and vertical separations. We also took into account the different transmitter loop pitch sign conventions used by FAS and the GA-LEI inversion algorithm (Appendix A, Section A.2.1).

5.2 Estimated data errors

To estimate noise in the data we used the additive and multiplicative noise model method developed by (Green and Lane, 2003). The noise model parameters were those used by Lane et al. (2004b), who derived the parameters from high altitude and repeat line data acquired on the Lower Balonne survey which was flown by the same TEMPEST aircraft and system immediately after the Honeysuckle Creek survey. The estimated parameters of the noise model are shown in the right hand columns of Table 2 above. The model estimates the standard deviation of the total noise in the $k^{th}$ channel to be,

$$e_k = \sqrt{a_k^2 + (0.01 \times m \times R_k^S)^2}$$

where, $a_k$ is the standard deviation of the additive noise in the $k^{th}$ window, $m$ is percentage multiplicative noise over all windows of the component, and $R_k^S$ is the secondary field in the $k^{th}$ window.

Additive noise is independent of ground conductivity and caused by factors such as atmospheric sferic activity, electronic noise and vibrational noise. Additive noise levels were determined from fully processed data recorded at high altitude.

Multiplicative noise is related to ground conductivity and is caused primarily by variations in system geometry that are not measured and accounted for. The multiplicative noise model parameter, which is expressed as a percentage of the secondary field response, was estimated from fully processed repeat line data recorded at survey altitude. The FAS height, pitch, roll and geometry corrected data were used for this purpose even though non-geometry corrected data are input into the inversion. The rationale for this is that, since the inversion algorithm uses measured
system geometry parameters and solves for unmeasured system geometry parameters, the effect of system geometry variation is largely accounted for. Thus noise model parameters estimated from geometry corrected data are likely to be more representative of inversion misfit errors.

5.3 Adjustments to altimeter data

It was reported by FAS in the survey data acquisition and processing report (Lawrence et al., 2001) that the radar altimeter was ‘intermittently suffering from a drift problem’ on some survey flights. These flights were not reflown. However FAS applied radar altimeter corrections to some lines based on data from an experimental laser altimeter that had been installed for the survey. The laser altimeter data itself was itself not of high enough quality to be used due to numerous spikes and missing values.

The transmitter loop height is calculated from the radar altimeter data and thus any errors in the altimeter data are reflected in conductivity estimates (Brodie and Lane, 2003). After our initial inversions, using the same settings as the preliminary inversion run (Section 0), numerous artefacts parallel to the flight lines were observed in images of the conductivity of the near surface layers. Since this is symptomatic of errors in altimeter data we attributed the artefacts to altimeter error.

To investigate the problem we performed several inversions on a sub sampled version of the dataset, then gridded, imaged and analysed the results. We made plots of the median value of the logarithm of Layer 1 conductivity along each line, computed over a narrow north-south corridor within the dataset, versus median line northing. Based on visual assessment of the magnitude of steps on the plots, and with the objective of minimising the artefacts in images of near surface conductivity, we empirically estimated corrections that had to be made to the transmitter loop height to remove the artefacts. The corrections were always constant over an entire flight or line. After several iterations of this empirical approach we were able to eliminate the majority of artefacts. The adjustments made to transmitter height data are tabulated in Table B.1 of Appendix B. Data input into the preliminary and final inversions used transmitter height data to which these adjustments had been applied.

The GA-LEI inversion algorithm does allow us the option to solve for the transmitter loop height in the inversion rather than use this empirical approach. We chose not to do this because of the potential parameter trade-offs (ambiguities), especially between transmitter loop height and transmitter to receiver vertical separation and conductivity. It is quite possible that the artefacts were not caused by altimeter error but by unknown variation in another system geometry parameter(s). However without any independent information to support that suggestion we assumed the artefacts were due to altimeter error for which there was some supporting evidence.

5.4 Model parameters

A multi-layer smooth-model formulation (Constable et al., 1987; Farquharson and Oldenburg, 1993) was used. The conductivity model had 25 layers that increased from 2 m thick at the surface and progressively got 10% thicker with depth. The layer thicknesses are shown in Table 3. During the inversion the layer thicknesses were kept fixed and we inverted for the base ten logarithms of the layer conductivities. The dielectric permittivity and magnetic permeability of each layer are set to that of free space ($\varepsilon=\varepsilon_0; \mu=\mu_0$).

We solved for three system geometry parameters; the transmitter to receiver horizontal in-line separation ($D_x$), the transmitter to receiver vertical separation ($D_z$), and the pitch of the receiver coil
assembly (RXₚ) as shown in Figure A.1. The other system geometry parameters were set to be either the values as measured by the radar altimeter (transmitter loop height) and gyroscopes (roll and pitch of the transmitter loop); or zero (yaw of the transmitter loop, transmitter to receiver horizontal transverse separation, roll and yaw of the receiver coil assembly).

<table>
<thead>
<tr>
<th>Layer number</th>
<th>Thickness (m)</th>
<th>Depth to top (m)</th>
<th>Depth to bottom (m)</th>
</tr>
</thead>
<tbody>
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<td>1</td>
<td>2.00</td>
<td>0.00</td>
<td>2.00</td>
</tr>
<tr>
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<td>4</td>
<td>2.66</td>
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<td>7</td>
<td>3.54</td>
<td>15.43</td>
<td>18.97</td>
</tr>
<tr>
<td>8</td>
<td>3.90</td>
<td>18.97</td>
<td>22.87</td>
</tr>
<tr>
<td>9</td>
<td>4.29</td>
<td>22.87</td>
<td>27.16</td>
</tr>
<tr>
<td>10</td>
<td>4.72</td>
<td>27.16</td>
<td>31.87</td>
</tr>
<tr>
<td>11</td>
<td>5.19</td>
<td>31.87</td>
<td>37.06</td>
</tr>
<tr>
<td>12</td>
<td>5.71</td>
<td>37.06</td>
<td>42.77</td>
</tr>
<tr>
<td>13</td>
<td>6.28</td>
<td>42.77</td>
<td>49.05</td>
</tr>
<tr>
<td>14</td>
<td>6.90</td>
<td>49.05</td>
<td>55.95</td>
</tr>
<tr>
<td>15</td>
<td>7.59</td>
<td>55.95</td>
<td>63.54</td>
</tr>
<tr>
<td>16</td>
<td>8.35</td>
<td>63.54</td>
<td>71.90</td>
</tr>
<tr>
<td>17</td>
<td>9.19</td>
<td>71.90</td>
<td>81.09</td>
</tr>
<tr>
<td>18</td>
<td>10.11</td>
<td>81.09</td>
<td>91.20</td>
</tr>
<tr>
<td>19</td>
<td>11.12</td>
<td>91.20</td>
<td>102.32</td>
</tr>
<tr>
<td>20</td>
<td>12.23</td>
<td>102.32</td>
<td>114.55</td>
</tr>
<tr>
<td>21</td>
<td>13.45</td>
<td>114.55</td>
<td>128.00</td>
</tr>
<tr>
<td>22</td>
<td>14.80</td>
<td>128.00</td>
<td>142.81</td>
</tr>
<tr>
<td>23</td>
<td>16.28</td>
<td>142.81</td>
<td>159.09</td>
</tr>
<tr>
<td>24</td>
<td>17.91</td>
<td>159.09</td>
<td>176.99</td>
</tr>
<tr>
<td>25</td>
<td>∞</td>
<td>176.99</td>
<td>∞</td>
</tr>
</tbody>
</table>

5.5 Preliminary inversion run

To construct a reference model for the preliminary inversion run we used both the average conductivity profile (Figure 2) and the spatially variable depth to the base of the sediments (dₚₑₐ) surface constructed with the GeoModeller software (Figure 3). The reference model layer conductivities were set to follow the piecewise linear approximation (blue trace) of the average conductivity profile in Figure 2.

The reference model represents a linear increase (in logarithm space) from 0.070 S/m at the surface to 0.250 S/m at 18 m. From 18 m to dₑₑ the constant value of 0.250 S/m was used, below which it was tapered back to a basement conductivity of 0.010 S/m. In the layers shallower than dₑₑ+20 m the conductivity model reference values were allowed to vary to reflect the variation in the
conductivity of the sediments (uncertainty 3.0 decades), but deeper than that a relatively small variation was allowed (uncertainty 0.5 decades).

The numerical formulae shown in Table 4 summarise the conductivity reference model rules applied. There are five vertices where depths, reference conductivity values and reference uncertainty values are assigned. The values assigned to a layer in the reference model were linearly interpolated (in logarithmic space) from the values at the vertex values according to the depth to the top of the layer.

The reference values for the transmitter to receiver horizontal in-line separation and the transmitter to receiver vertical separation system geometry parameters were set to be the values as estimated in the standard data processing applied by FAS. A value of zero was used as the reference value for the pitch of the receiver coil assembly parameter. The uncertainty values were as shown in Table 5.

**Table 4**  Conductivity reference model setting for the preliminary inversion run.

<table>
<thead>
<tr>
<th>Vertex number</th>
<th>Depth (m)</th>
<th>Reference conductivity (S/m)</th>
<th>Reference conductivity uncertainty (log_{10} S/m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>v1</td>
<td>0</td>
<td>0.070</td>
<td>3.0</td>
</tr>
<tr>
<td>v2</td>
<td>18</td>
<td>0.025</td>
<td>3.0</td>
</tr>
<tr>
<td>v3</td>
<td>d_{sed}</td>
<td>0.025</td>
<td>3.0</td>
</tr>
<tr>
<td>v4</td>
<td>d_{sed+20}</td>
<td>0.010</td>
<td>0.5</td>
</tr>
<tr>
<td>v5</td>
<td>∞</td>
<td>0.010</td>
<td>0.5</td>
</tr>
</tbody>
</table>

**Table 5**  System geometry reference model setting for the preliminary inversion run.

<table>
<thead>
<tr>
<th>Variable</th>
<th>Reference value</th>
<th>Reference value uncertainty</th>
</tr>
</thead>
<tbody>
<tr>
<td>transmitter to receiver horizontal in-line separation (D_x)</td>
<td>as estimated in FAS data processing</td>
<td>2 m</td>
</tr>
<tr>
<td>transmitter to receiver vertical separation (D_z)</td>
<td>as estimated in FAS data processing</td>
<td>2 m</td>
</tr>
<tr>
<td>receiver coil assembly pitch (RX_p)</td>
<td>0°</td>
<td>4°</td>
</tr>
</tbody>
</table>
The automated routine described in Section 6.5 (using a conductivity threshold $c^{\text{thresh}} = 0.030 \text{ S/m}$) was used to estimate the depth to basement ($d_{pb}$) from the results of the preliminary inversion run. The average conductivity ($c_{ps}$) of the interval from surface to $d_b$ was then calculated. Both $d_{pb}$ and $c_{ps}$ were gridded to 40 m cell size and spatially smoothed using sequentially applied 7×7 (240×240 m) median then averaging kernel filters. Images of these quantities are shown in Figure 4.

5.6 Final inversion run

The rationale behind the production of the smoothed grids of the automated estimated depth to basement ($d_b$) and average conductivity of the sediments ($c_{ps}$) from the preliminary inversion run was to introduce spatial context, which is not offered by a survey wide average conductivity profile, to the reference and starting models for the final inversion run.

We used a conductivity reference model that increased from the minimum of $c_{ps}$ and 0.070 (S/m) at the surface (the surface value from survey wide average) to $c_{ps}$ at 18 m depth. From 18 m to the depth $d_b$=20 the average sediment conductivity was used, below which it was tapered back to a basement conductivity of 0.010 S/m over a 20 m interval. This is demonstrated schematically by the red profile on Figure 5 which represents an example where $d_b = 70$ m and $c_{ps} = 0.220 \text{ S/m}$.

In places where the estimated depth to basement was shallow ($d_b<25$) we enforced minimum depths at which the tapering from average sediment conductivity to basement conductivity began (19 m) and ended (25 m). This is demonstrated schematically by the blue profile on Figure 5 which represents an example of a reference model at a location with shallow basement in a resistive area where $d_b = 10$ m and $c_{ps} = 0.040 \text{ S/m}$. The minimum depth rule allows at least some tapering of the reference conductivity profile to prevent non-smooth starting and reference models occurring, which are not ideal because they can cause conflict between reference model and smoothness constraints and lead to inversion instability.

The numerical formulae shown in Table 6 summarise the rules applied. There are five vertices where depths, reference conductivity values and reference uncertainty values are assigned. The values assigned to a layer in the reference model were linearly interpolated (in logarithmic space)
from the vertex values according to the depth to the top of the layer. Values for the system geometry reference models parameters were set in precisely the same way as for the preliminary inversion run, which are detailed in Table 5.

In the final inversion run we used values of $\alpha_c = 1.0$, $\alpha_s = 0.1$, and $\alpha_r = 100,000$ for the model regularisation factors that control the relative weighting of components of the inversion objective function described in Section A.3 of Appendix A.

All 444,524 samples in the survey were inverted. The inversion was run on 80 CPUs of Geoscience Australia’s linux cluster computer called Tornado under the Message Passing Interface (Message Passing Interface Forum, 1995) parallel computation paradigm. The elapsed time was 67:51 hours.

<table>
<thead>
<tr>
<th>Vertex number</th>
<th>Depth (m)</th>
<th>Reference conductivity (S/m)</th>
<th>Reference conductivity uncertainty ($\log_{10} S/m$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>v1</td>
<td>0</td>
<td>min($c_{ps}$ &amp; 0.070)</td>
<td>1.0</td>
</tr>
<tr>
<td>v2</td>
<td>18</td>
<td>$c_{ps}$</td>
<td>1.0</td>
</tr>
<tr>
<td>v3</td>
<td>max(19 &amp; $d_{pb}$−20)</td>
<td>$c_{ps}$</td>
<td>1.0</td>
</tr>
<tr>
<td>v4</td>
<td>max(25 &amp; $d_{pb}$)</td>
<td>0.010</td>
<td>0.3</td>
</tr>
<tr>
<td>v5</td>
<td>$\infty$</td>
<td>0.010</td>
<td>0.3</td>
</tr>
</tbody>
</table>
6 Post inversion processing

6.1 Comparison with downhole logs

The inversion results have been compared to the downhole conductivity logs acquired in the survey area. For each borehole the downhole log and the inverted conductivity profile from the closest AEM sample is plotted in Figure 6 and continued in Figure 7. The distance from the borehole to the closest AEM sample is also shown on the plots.
Figure 6  Comparisons of downhole log conductivity and GA-LEI estimated conductivity – Part 1.
Figure 7  Comparisons of downhole log conductivity and GA-LEI estimated conductivity – Part 2.

Figure 8 shows a scatter plot comparison between conductivities measured by downhole conductivity logging and estimates from the GA-LEI inversion. Each point represents the average conductivity over 5 m depth interval intersected in the boreholes. Note that the black diagonal line is not a line of best fit, but is the line of 1:1 correspondence along which the scatter points would ideally lie.

A comparison between downhole logs, the GA-LEI inversions and the previous four (see Section 1) generations of conductivity estimates, (i) FAS EmFlow CDT, (ii) Christensen EmFlow CDT, (iii) Sattel LEI and (iv) Sattel HPRG LEI are shown in Appendix C. Note that we only had access to gridded data for the Christiansen EmFlow CDT, which is the reason why those profiles only extend to 100 m depth.
Figure 8 Scatter plot comparisons between conductivities measured by downhole conductivity logging and estimates from the GA-LEI inversion.

6.2 Gridding and microlevelling

The logarithm of all 25 layer conductivities were gridded to a square 40 m cell size from the point located inverted sample data using the minimum curvature gridding. These grids were micro-levelled to reduce the effect of artefacts aligned in the flight line direction (Minty, 1991). The decorrugation filter was 5000 m long and 400 m wide and had a tolerance of 1.0 decades. The corrections were applied back to the point located data. The micro-levelled point located data were then gridded, in the same manner as the non micro-levelled data, to produce the final logarithm of layer conductivity grids. These were converted back to linear conductivity. Gridding and microlevelling operations were carried out using the Intrepid Software package (v4.1 Release Build 125-4/12/2007).

6.3 Depth slices

A conductivity depth slice is the average estimated conductivity over a given depth interval. The calculation is a simple weighted average of all the layers that intersect the depth interval. For example by inspection of Table 3 it is straightforward to see that the 5 m to 10 m depth slice would be calculated by,

\[
\frac{(6.62 - 5) \times \text{layer 3 conductivity} + (2.66) \times \text{layer 4 conductivity} + (10 - 9.28) \times \text{layer 5 conductivity}}{10 - 5}
\]

Depth slice grids were calculated directly from the micro-levelled layer conductivity grids. The following depth slice grids were produced 0-5 m, 5-10 m, 10-15 m, 15-20 m, 20-30 m, 30-40 m, 40-60 m, 60-80 m, 80-100 m, 100-150 m, and 150-200 m. Example images of four conductivity depth slice grids are shown in Figure 9.
Conductivity-depth sections were produced for each flight line. These sections are graphical representations of the estimated conductivity in a vertical slice along the line of best fit passing through the flight line. Sections were produced by first applying a five point (~62m) along line median filter to the point located layer conductivity data. These data were then resampled onto the lines of best bit using nearest neighbour interpolation.

Downhole conductivity log data are also included on the sections if the borehole lies within 200 metres of the line of best fit. These conductivity log data are presented as coloured columns with the colour coding equivalent to that on the section. The distance from the borehole to the line of best fit is also displayed. We have also included a line which represents the automatically interpreted basement depth generated by the routine described in Section 6.5. Example sections for three flight lines are shown in Figure 10.

**Figure 9** Images of four selected conductivity depth slices.

### 6.4 Sections

Conductivity-depth sections were produced for each flight line. These sections are graphical representations of the estimated conductivity in a vertical slice along the line of best fit passing through the flight line. Sections were produced by first applying a five point (~62m) along line median filter to the point located layer conductivity data. These data were then resampled onto the lines of best bit using nearest neighbour interpolation.

Downhole conductivity log data are also included on the sections if the borehole lies within 200 metres of the line of best fit. These conductivity log data are presented as coloured columns with the colour coding equivalent to that on the section. The distance from the borehole to the line of best fit is also displayed. We have also included a line which represents the automatically interpreted basement depth generated by the routine described in Section 6.5. Example sections for three flight lines are shown in Figure 10.
Figure 10    Images of three selected conductivity depth sections.
6.5 Automatically interpreted depth to basement

A routine was devised for automatically picking a depth to basement surface from the AEM inversion results. The routine began by finding a depth $d_{\text{thresh}}$ below which estimates in the inverted vertical conductivity profile fall below a threshold conductivity $c_{\text{thresh}}$ for each AEM sample. These were converted to estimated elevations ($e_{\text{thresh}}$) of the basement relative to the Australian height datum (AHD). The flight line profiles of $e_{\text{thresh}}$ were then smoothed by sequential application of a 31 point (~375 m) median filter followed by a 51 point (~625 m) averaging filter.

These smoothed data were then gridded to a cell size of 40 m and micro-levelled using a decorrugation filter 5000 m long and 400 m wide with a tolerance of 30 m. The micro-levelled basement elevation estimates were converted back to basement depth estimates. Both micro-levelled basement depths and elevations were gridded to a cell size of 40 m.

We calibrated the result by trialling several choices of the threshold conductivity $c_{\text{thresh}}$ and making comparisons of the resultant basement depth estimates with the borehole stratigraphic information described in Section 0. We chose to use the trialled value of $c_{\text{thresh}} = 0.140 \text{ S/m}$, which gave the best correlation between the bore interpreted basement depth and the automatically interpreted basement depth. For an area in the northwest of the survey area, which is known to have fresher ground waters (outlined by a white polygon on Figure 12), we chose a lower threshold conductivity of $c_{\text{thresh}} = 0.030 \text{ S/m}$.

A scatter plot of the correlations for the final basement depth estimates is shown in Figure 11. Note that the black diagonal line is not a line of best fit, but is the line of 1:1 correspondence along which the scatter points would ideally lie. Images of the final automatically interpreted basement depth and elevation surfaces are shown in Figure 12.
Figure 11  Correlation between the borehole stratigraphy interpreted basement depths and automated AEM inversion interpreted basement depths.

![Correlation between the borehole stratigraphy interpreted basement depths and automated AEM inversion interpreted basement depths.](image)

Figure 12  Gradient enhanced images of the estimated depth and elevation of the basement surface grids using the automated basement picking routine. Gradient enhancement is by an east-west sun angle kernel.

![Gradient enhanced images of the estimated depth and elevation of the basement surface grids using the automated basement picking routine. Gradient enhancement is by an east-west sun angle kernel.](image)
7 References


Smith, R.S., 2001a. On removing the primary field from fixed wing time-domain airborne electromagnetic data: some consequences for quantitative modelling, estimating bird position and detecting perfect conductors: Geophysical Prospecting, 49, 405-416.


Appendix A – GA-LEI Inversion of TEMPEST Data

A.1 Introduction

The GA-LEI inversion program is capable of inverting data from most airborne time-domain AEM systems. It has the capability of inverting for layer conductivities, layer thicknesses, and system geometry parameters, or some subset of these. There are options to use a multi-layer smooth-model formulation (Constable et al., 1987) or a few-layer blocky-model formulation (Sattel, 1998). For the sake of simplicity, only the aspects of the algorithm that are relevant to the inversion of TEMPEST data using a multi-layer smooth-model are described.

TEMPEST data consist of a collection (tens of thousands to millions) of point located multi-channel samples acquired at 0.2 s (approximately 12 m) intervals along survey flight lines. The algorithm independently inverts each sample. The data inputs to the inversion of each sample are the observed total (primary plus secondary) field X-component and Z-component data. Auxiliary information input into the algorithm are the measured and assumed elements of the system geometry, the thicknesses of the layers, and prior information on the unmeasured elements of the system geometry and ground conductivity. The unknowns solved for in the inversion (outputs) are the electrical conductivity of the layers and the unmeasured elements of the system geometry.

Since each sample is inverted independently, the user may elect to invert all samples or some subset of them. The inversion of each sample results in an estimate of a one dimensional (1D) conductivity structure associated with that sample. Each estimated 1D conductivity structure, although theoretically laterally constant and extending infinitely in all directions, is only supported by the data within the system footprint which is approximately a square of side length 470 m centred about the sample point (Reid and Vrbančič, 2004). So by progressively inverting all the samples and stitching together the resultant 1D conductivity structures a depiction of the overall laterally variable 3D conductivity structure is built up.

A.2 Formulation

Figure A.1 shows the overall framework under which the inversion of a single airborne sample is carried out. The elements of the figure are progressively described in the following sections.

A.2.1 Coordinate system

Since each sample is inverted separately the coordinate system is different for the inversion of each sample. A right handed \(xyz\) Cartesian coordinate system is used. The origin of the coordinate system is on the Earth’s surface directly below the centre of the transmitter loop. The \(x\)-axis is in the direction of flight of the aircraft at that sample location, the \(y\)-axis is in the direction of the left wing and the \(z\)-axis is directed vertically upwards.

A.2.2 System geometry

The centre of the transmitter loop is located at \((0, 0, TX_h)\). Roll of the transmitter loop \((TX_r)\) is defined as anti-clockwise rotation, about an axis through \((0, 0, TX_h)\) and parallel to the \(x\)-axis, so that a positive roll will bring the left wing up. Pitch of the transmitter loop \((TX_p)\) is defined as anti-clockwise rotation, about an axis through \((0, 0, TX_h)\) and parallel to the \(y\)-axis, so that positive pitch will bring the aircraft’s nose down. Yaw of the transmitter loop \((TX_y)\) is defined as anti-clockwise rotation, about an axis through \((0, 0, TX_h)\) and parallel to the \(z\)-axis, so that a positive yaw would turn the aircraft left. However since the \(x\)-axis is defined to be in the direction of flight at each
sample, the transmitter loop yaw is always zero by definition. The order of operations for calculating the vector orientations is to apply the pitch, roll then yaw rotations respectively.

The position of the receiver coils relative to the transmitter loop is defined by the transmitter to receiver horizontal inline separation (\(D_x\)), the transmitter to receiver horizontal transverse separation (\(D_y\)), and the transmitter to receiver vertical separation (\(D_z\)). The receiver coils are thus located at \((D_x, D_y, RX_h=TX_h+D_z)\). The receiver coils are always behind and below the aircraft (\(D_x<0, D_z<0\)). The receiver coils’ roll (\(RX_r\)), pitch (\(RX_p\)) and yaw (\(RX_y\)) have the same rotational convention as for the transmitter loop except that they are rotations about the point \((D_x, D_y, D_z)\). The receiver coils are always assumed to be located on the y-axis (\(D_y = 0\)) and to have zero yaw (\(RX_y = 0\)). Although this is not in reality the case, the position and orientation is not measured and there is not enough information available to solve for these since Y-component data is not available.

Figure A.1  Schematic representation of the framework for GA-LEI inversion of TEMPEST AEM data. Red elements are the unknowns to be solved for.
Note that transmitter loop pitch data supplied by Fugro Airborne Surveys in processed TEMPEST data uses the convention where a positive transmitter pitch is nose up, and accordingly the supplied pitch is reversed in sign before being used in the inversion algorithm.

A.2.3 Layered earth

The layered earth model is independent at each inverted sample location. The layered earth consists of $N_L$ horizontal layers stacked on top of each other in layer cake fashion. The $k^{th}$ layer has constant thickness $t_k$ and the bottom layer is a halfspace that has infinite thickness ($t_{NL} = \infty$), extending to infinite depth. The electrical conductivity of the $k^{th}$ layer is $c_k$ and it is constant throughout the layer. The magnetic permeability of all layers is assumed to be equal to the magnetic permeability of free space $\mu_0$. The dielectric permittivity of all layers is assumed to be equal to the permittivity of free space $\varepsilon_0$.

A.2.4 Data

Part of the TEMPEST data processing sequence involves partitioning the total (secondary plus primary) field response that is actually observed into estimates of the unknown primary and secondary field components. Then an estimate of the transmitter to receiver horizontal in-line and vertical separations $D_x$ and $D_z$ are made from the partitioned primary field component. The procedure uses the measured transmitter pitch ($TX_p$) and roll ($TX_r$) and assumes the receiver coils are flying straight, level and directly behind the aircraft ($D_y=0$, $RX_x=0$, $RX_p=0$, and $RX_y=0$). It is the estimated secondary field data, the measured elements of the system geometry ($TX_h$, $TX_p$, $TX_r$, and $TX_y$) and the associated estimates of the unmeasured elements of the system geometry ($D_x$ and $D_z$) that are delivered to clients. Implicit in the delivered dataset are the assumed elements of the system geometry ($D_y=0$, $RX_x=0$, $RX_p=0$, and $RX_y=0$). However the estimated primary field data are not delivered to clients.

Since the GA-LEI algorithm makes its own estimate of system geometry as part of the inversion procedure it works with total field data. The input data are the total (primary plus secondary) field X-component and Z-component data. Therefore the total field data are first reconstructed. This is a simple matter of recomputing the primary field from magnetic dipole formulae (Wait, 1983) using the delivered (measured, estimated and assumed) elements of the system geometry then adding them to the delivered secondary field data. Note that the height, pitch, roll and geometry corrected data that are usually delivered as part of TEMPEST datasets are not used because the GA-LEI algorithm makes its own estimate of system geometry as part of the inversion procedure.

The reconstructed X-component and Z-component total field data for the $k^{th}$ window are $X_k = X^p + X^s_k$ and $Z_k = Z^p + Z^s_k$ respectively. Here the super scripts $^p$ and $^s$ represent primary and secondary field components. Since the TEMPEST system has $NW = 15$ windows, the observed data vector of length $ND = 2NW = 30$ used in the inversion is,

$$d^{obs} = [X_1, X_2 \cdots X_{NW}, Z_1, Z_2 \cdots Z_{NW}]^T,$$

where $^T$ represents the matrix and vector transpose operator.

Errors on the data are calculated outside of the program and input along with the data. Errors are assumed to be uncorrelated and Gaussian distributed. They are estimated as standard deviations of the Gaussian error distribution for each window and receiver component. Typically errors are calculated from the parameters of an additive plus multiplicative noise model (Green and Lane, 2003). Parameters of the noise model are determined from analysis of high altitude and repeat line
data. If \( X_k^{err} \) and \( Z_k^{err} \), represent the estimated standard deviation of the error in the \( k^{th} \) window of the X-component and Z-component data respectively then the data error vector of length \( N_D=30 \) is,

\[
d^{err} = [X_1^{err} \ X_2^{err} \ldots X_{N_w}^{err} \ Z_1^{err} \ Z_2^{err} \ldots Z_{N_w}^{err}]^T.
\] (2)

### A.2.5 Model parameterisation

The unknown model parameter vector \( (m) \) to be solved for in the inversion is comprised of earth model parameters and system geometry model parameters.

For the inversion of the TEMPEST dataset described here we choose to use a multi-layer smooth-model formulation (Constable et al., 1987) rather than a few-layer blocky-model formulation (Sattel, 1998). Therefore we solve for the \( N_L \) conductivities of the layers but not the thicknesses. The layer thicknesses are inputs into the algorithm and are kept fixed throughout. To maintain positivity of the layer conductivities we actually invert for the base ten logarithms of the conductivities of each layer.

We solve for \( N_G=3 \) system geometry parameters; the transmitter to receiver horizontal in-line separation (\( D_x \)), the transmitter to receiver vertical separation (\( D_z \)), and the pitch of the receiver coil assembly (\( RX_p \)).

The unknown model parameter vector of length \( N_P=N_G+N_L \) to be solved for is the concatenated vector of log base ten layer conductivities \( \mathbf{c} = [\log_{10} c_1 \ \log_{10} c_2 \ \cdots \log_{10} c_{N_L}]^T \) and the geometry parameters \( g = [D_x \ D_z \ RX_p]^T \), such that,

\[
m = [\mathbf{c} \ | \ g] = [\log_{10} c_1 \ \log_{10} c_2 \ \cdots \log_{10} c_{N_L} \ D_x \ D_z \ RX_p]^T
\] (3)

### A.2.6 Forward model and derivatives

The forward model is the non-linear multi-valued function,

\[
f(m) = [f_1(m \ | \ p) \ f_2(m \ | \ p) \cdots f_{ND}(m \ | \ p)],
\] (4)

which for a given a set of model parameters \( (m) \) calculates the theoretical total field data equivalent to that which would be produced for an ideal system, after the measurement and transformation by the data processing steps (Lane et al., 2000). Here each \( f_i(m \ | \ p) \) is a function, not only of the layer conductivities and system geometry parameters in the inversion model vector \( m \), but also of several other fixed parameters \( p \) (layer thicknesses; transmitter height, pitch and roll; receiver roll and yaw, transmitter to receiver horizontal transverse separation; system waveform and window positions etc.).

The implementation of (4) is based upon the formulation of Wait (1982) in which he develops the frequency-domain expressions for the magnetic fields due to vertical and horizontal magnetic dipole sources above a horizontally layered medium. The formulation does not account for the contribution due to displacement currents. We also assume that effects of dielectric permittivity and magnetic susceptibility are negligible compared to electrical conduction, and set each layer’s dielectric permittivity and magnetic permeability to that of free space (\( \varepsilon_k = \varepsilon_0; \mu_k = \mu_0 \)).

The full transient (0.04 s) equivalent square current waveform, to which TEMPEST data are processed, was linearly sampled at 75,000 Hz (3000 samples) and transformed to the frequency domain via fast Fourier transform (FFT). Using Wait’s expressions the secondary B-field was calculated for 21 discrete frequencies between 25 Hz and 37,500 Hz (~6.5 logarithmically equi-spaced frequencies per decade). The inphase and quadrature parts of each component were then
individually splined to obtain linearly spaced values at the same frequencies as the nodes of the FFT transformed current waveform. Complex multiplication of splined B-field with the FFT transformed current waveform, followed by inverse FFT, yielded the B field transient response.

The transient was then windowed into the 15 windows by averaging those samples that fell within each window. The primary field, which is constant over all 15 windows, was then computed from Wait’s expressions and added to yield the total field window response in the x-axis and z-axis directions. Finally these were rotated to be aligned with the X-component receiver coil’s axis and Z-component receiver coil’s axis according to the receiver pitch model parameter (RXp) to yield \( f(m) \).

The inversion also requires the partial derivatives of \( f(m) \) with respect to the model parameters, see equation (19) These were all calculated analytically. For computation of Wait’s coefficient \( R_0 \), we took advantage of the propagation matrix method (Farquharson et al., 2004) because it is efficient for computation of the partial derivatives with respect to the multiple layer conductivities.

### A.2.7 Reference model

The algorithm uses the concept of a reference model (Farquharson and Oldenburg, 1993) to incorporate prior information from downhole conductivity logs or lithologic/stratigraphic logging in order to improve inversion stability and to reduce the trade-off between parameters that are not well resolved independently. Since prior information is not available everywhere within the survey area, and the inversions are carried out in independent sample by sample fashion, it is not plausible to place hard reference model constraints on the model parameters. Instead the reference model provides a soft or probabilistic constraint only. If, from prior information, it is concluded that the likely distribution of the model parameter \( m_k \) is a Gaussian distribution with mean \( m_k^{ref} \) and standard deviation \( m_k^{unc} \), then we would define the reference model vector as,

\[
m^{ref} = [l_1^{ref} l_2^{ref} \cdots l_{Nc}^{ref} \ D_x^{ref} \ D_z^{ref} \ RX_p^{ref}]^T
\]

and the reference model uncertainty vector as,

\[
m^{unc} = [l_1^{unc} l_2^{unc} \cdots l_{Nc}^{unc} \ D_x^{unc} \ D_z^{unc} \ RX_p^{unc}]^T
\]

The reference model mean values and uncertainties are inputs to the inversion algorithm and they may be different from sample to sample. The uncertainty values assigned to the reference model control the amount of constraint that the reference model places on the inversion results. A large uncertainty value for a particular parameter implies that the assigned reference model mean value is not well known and thus is allowed to vary a long way from the mean. On the other hand a low uncertainty implies the parameter is well known.

### A.3 Objective function

The inversion scheme minimises a composite objective function of the form,

\[
\Phi = \Phi_d + \lambda \left( \alpha_c \Phi_c + \alpha_g \Phi_g + \alpha_v \Phi_v \right)
\]

where \( \Phi_d \) is a data misfit term, \( \Phi_c \) is a layer conductivity reference model misfit term, \( \Phi_g \) is a system geometry reference model misfit term, and \( \Phi_v \) is a vertical roughness of conductivity term. The relative weighting of the data misfit \( \Phi_d \) and the collective model regularisation term,

\[
\Phi_m = \alpha_c \Phi_c + \alpha_g \Phi_g + \alpha_v \Phi_v
\]
is controlled by the value of regularisation factor $\lambda$. The three model regularisation factors $\alpha_c$, $\alpha_g$ and $\alpha_s$ control the relative weighting within the model regularisation term $\Phi_m$. The algorithm requires that the $\alpha$ values be set by the user on a application by application basis and they remain fixed throughout the inversion. However the $\lambda$ is automatically determined within the algorithm by the method described in section A.4.2.

### A.3.1 Data misfit

The data misfit $\Phi_d$ is a measure of the misfit, between the data ($d^{obs}$) and the forward model of the model parameters ($f(m)$), normalised by the expected error and the number of data. It is defined as,

$$\Phi_d = \frac{1}{N_D} \sum_{k=1}^{N_D} \left( \frac{d^{obs}_k - f(m)}{d^{err}_k} \right)^2$$

$$= \left[ d^{obs} - f(m) \right]^T W_d \left[ d^{obs} - f(m) \right]$$

The diagonal $N_D \times N_D$ matrix $W_d$ is,

$$W_d = \frac{1}{N_D} \begin{bmatrix} 1 \left( d^{err}_1 \right)^2 \\ 1 \left( d^{err}_2 \right)^2 \\ \vdots \\ 1 \left( d^{err}_{N_D} \right)^2 \end{bmatrix}$$

### A.3.2 Conductivity reference model misfit

The conductivity reference model misfit term $\Phi_c$ is a measure of the misfit, between the logarithmic conductivity model parameters ($l_c$) and the corresponding layer reference model values ($l_c^{ref}$) normalised by the layer thicknesses and reference model uncertainty. It is defined as,

$$\Phi_c = \frac{1}{T N_L} \sum_{k=1}^{N_L} \frac{t_k}{T/N_L} \left( \frac{l_c^{ref}_k - l_c^{unc}_k}{l_c^{ref}_k} \right)^2$$

$$= \left[ m^{ref} - m \right]^T W_c \left[ m^{ref} - m \right]$$

where $T = \sum_{k=1}^{N_L} t_k$, and the diagonal $N_p \times N_p$ matrix $W_c$ is,
Since the bottom layer is infinitely thick, for the purposes of this term we set $t_{N_L} = [t_{N_L-1}]^2/t_{N_L-2}$.

**A.3.3 System geometry reference model misfit**

The system geometry reference model misfit term $\Phi_g$ is a measure of the misfit, between the system geometry model parameters ($\mathbf{g}$) and the corresponding system geometry reference model values ($\mathbf{g}^{\text{ref}}$) normalised by the number of unknown system geometry parameters ($N_G=3$) and their uncertainty. It is defined as,

$$\Phi_g = \frac{1}{N_G} \sum_{k=1}^{N_G} \left( \frac{g_k^{\text{ref}} - g_k}{g_k^{\text{unc}}} \right)^2.$$

The diagonal $N_p \times N_p$ matrix $\mathbf{W}_g$ is,

$$\mathbf{W}_g = \frac{1}{N_G} \begin{bmatrix} 1 & & & \frac{1}{(D_x^{\text{unc}})^2} & \frac{1}{(D_y^{\text{unc}})^2} & \frac{1}{(RX_p^{\text{unc}})^2} \\ & 0 & & & & \\ & & \ddots & & & \\ & & & 0 & & \\ & \frac{1}{(D_x^{\text{unc}})^2} & & & & \\ & & & & \frac{1}{(D_y^{\text{unc}})^2} & \\ & & & & & \frac{1}{(RX_p^{\text{unc}})^2} \end{bmatrix}.$$

**A.3.4 Vertical roughness of conductivity**

The vertical roughness of conductivity term $\Phi_v$ is a measure of the roughness of the conductivity profile. It sums the squared second derivative of the logarithm of the vertical conductivity profile,
approximated by finite difference over adjacent layer triplets, taking into account the distance between layer centres. The result is normalised by the number of triplets \( N_L - 2 \) and is defined as,
\[
\Phi_v = \frac{1}{N_L - 2} \sum_{k=2}^{N_L-1} \left( \frac{l_{c_{k-1}} - l_{c_k}}{1/2(t_{k-1} + t_k)} - \left( \frac{l_{c_k} - l_{c_{k+1}}}{1/2(t_k + t_{k+1})} \right) \right)^2
\]
\[
= \mathbf{m}^T \mathbf{L}_v^T \mathbf{L}_v \mathbf{m}
\] (15)
where the \( N_L - 2 \times N_p \) matrix \( \mathbf{L}_v \) is,
\[
\mathbf{L}_v = \frac{1}{N_L - 2} \begin{bmatrix}
\frac{1}{(t_1 + t_2)} & \left( \frac{-1}{(t_1 + t_2)} + \frac{-1}{(t_2 + t_3)} \right) & \frac{1}{(t_2 + t_3)} & \left( \frac{-1}{(t_2 + t_3)} + \frac{-1}{(t_3 + t_4)} \right) & \frac{1}{(t_3 + t_4)} & \cdots & \cdots & \cdots \\
\frac{1}{(t_2 + t_3)} & \left( \frac{-1}{(t_2 + t_3)} + \frac{-1}{(t_3 + t_4)} \right) & \frac{1}{(t_3 + t_4)} & \cdots & \cdots & \cdots & \cdots & \cdots \\
\vdots & \vdots & \vdots & \ddots & \ddots & \ddots & \ddots & \ddots \\
0 & 0 & 0 & \cdots & \cdots & \cdots & \cdots & \cdots \\
0 & 0 & 0 & \cdots & \cdots & \cdots & \cdots & \cdots \\
\end{bmatrix}
\] (16)

Again for the purposes of this term we set \( t_{N_L} = [t_{N_L-1}]^2/t_{N_L-2} \).

A.4 Minimisation scheme

A.4.1 Linearisation

To minimise the objective function \( \Phi \), a linearised gradient based iterative minimisation scheme is used. Collection of the matrix notation misfit term equations (9), (11), (13) and (15) that make up \( \Phi \) allows us to write,
\[
\Phi(\mathbf{m}) = [\mathbf{d}^{\text{obs}} - \mathbf{f}(\mathbf{m})]^T \mathbf{W}_d [\mathbf{d}^{\text{obs}} - \mathbf{f}(\mathbf{m})] + \cdots \nonumber
\]
\[
\lambda \left[ \alpha_c [\mathbf{m}^{\text{ref}} - \mathbf{m}]^T \mathbf{W}_c [\mathbf{m}^{\text{ref}} - \mathbf{m}] + \alpha_g [\mathbf{m}^{\text{ref}} - \mathbf{m}]^T \mathbf{W}_g [\mathbf{m}^{\text{ref}} - \mathbf{m}] + \alpha_m \mathbf{m}^T \mathbf{L}_v^T \mathbf{L}_v \mathbf{m} \right]
\]
(17)

The inversion begins by setting the initial estimate of the model parameters to the reference model \( \mathbf{m}_0 = \mathbf{m}^{\text{ref}} \). During the \( n^{th} \) iteration the current estimate of the model parameters \( \mathbf{m}_n \) is perturbed by the parameter change vector,
\[
\Delta \mathbf{m}_n = \mathbf{m}_{n+1} - \mathbf{m}_n
\] (18)

The forward model at the new set of model parameters \( \mathbf{m}_{n+1} \) is approximated by a Taylor series expansion about \( \mathbf{m}_n \), which, after excluding high order terms reduces to,
\[
\mathbf{f}(\mathbf{m}_{n+1}) \approx \mathbf{f}(\mathbf{m}_n) + \mathbf{J}_n (\mathbf{m}_{n+1} - \mathbf{m}_n)
\] (19)

where \( \mathbf{J}_n = \partial \mathbf{f}(\mathbf{m})/\partial \mathbf{m} \) is the Jacobian matrix whose \( i^{th}, j^{th} \) element is the partial derivative of the \( i^{th} \) datum with respect to the \( j^{th} \) model parameter evaluated at \( \mathbf{m}_n \) in model space. Making use of (19) and substituting \( \mathbf{m} = \mathbf{m}_{n+1} \), allows (17) to be rewritten as,
\( \Phi(m_{n+1}) = \left[ d^\text{obs} - f(m_n) - J_n(m_{n+1} - m_n) \right]^T W_d \left[ d^\text{obs} - f(m_n) - J_n(m_{n+1} - m_n) \right] + \cdots \)

\[ \lambda \left[ \alpha_c [m^\text{ref} - m_{n+1}]^T W_c [m^\text{ref} - m_{n+1}] + \alpha_g [m^\text{ref} - m_{n+1}]^T W_g [m^\text{ref} - m_{n+1}] + \alpha_c m_{n+1}^T L_c L_c m_{n+1} \right] \] (20)

Since the value of \( \Phi \) will be minimised when \( \partial \Phi / \partial m_{n+1} = 0 \), so we differentiate (20) with respect to \( m_{n+1} \) and set the result to zero and get,

\[ 0 = -2J_n^T W_d \left[ d^\text{obs} - f(m_n) - J_n(m_{n+1} - m_n) \right] + \cdots \]

\[ \lambda \left[ -2\alpha_c W_c [m^\text{ref} - m_{n+1}] - 2\alpha_g W_g [m^\text{ref} - m_{n+1}] + 2\alpha_c L_c^T L_c m_{n+1} \right] \] (21)

Collecting terms in the unknown vector \( m_{n+1} \) on the left hand side yields,

\[ \left[ J_n^T W_d J_n + \lambda (\alpha_c W_c + \alpha_g W_g + \alpha_c L_c^T L_c) \right] m_{n+1} = \cdots \]

\[ J_n^T W_d \left[ d^\text{obs} - f(m_n) + J_n m_n \right] + \lambda \left[ \alpha_c W_c + \alpha_g W_g \right] m^\text{ref} \] (22)

Since (22) is in the familiar form of a system of linear equations \( (A m_{n+1} = b) \) we are able to solve for \( m_{n+1} \) using a variety of linear algebra methods. We use Cholesky decomposition.

### A.4.2 Choice of the value of \( \lambda \)

An initial value of \( \lambda \) is chosen such that the data and model objective functions will have approximately equal weight. This is automatically realised by computing the ratio of the data and model objective functions, from the reference model perturbed by 1%, and computing the ratio of the data and model misfits,

\[ \lambda_{\text{start}} = \frac{\Phi_d(f(1.01 \times m_0))}{\Phi_m(1.01 \times m_0)}. \] (23)

Then at each iteration the inversion employs a 1D line search where, in solving for \( m_{n+1} \) in (22) different values of \( \lambda \) are trialled, until a value of \( \lambda_n \) is found such that,

\[ \Phi_d(f(m_{n+1})) \approx \Phi_d^{\text{arg min}} = 0.7 \times \Phi_d(f(m_n)), \] (24)

thus reducing \( \Phi_d \) to 0.7 of its previous value.

### A.4.3 Convergence criterion

The iterations continue until the inversion terminates when one of the following conditions is encountered;

- \( \Phi_d \) reaches a user defined minimum value \( \Phi_d^{\text{min}} = 1 \);
- \( \Phi_d \) has been reduced by less than 1% in two consecutive iterations;
- \( \Phi_d \) can no longer be reduced; or

the number of iterations reaches a maximum of 100 iterations.

### A.5 References


### Appendix B – Transmitter height adjustments

Table B.1 Adjustments (in metres) made to the transmitter height values

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Figure C.1  Comparison between downhole conductivity logs and the five types of conductivity estimates for bores HC1, HC2, HC3 and HC4.
Figure C.2 Comparison between downhole conductivity logs and the five types of conductivity estimates for bores HC5, HC6, HC7 and HC8.
Figure C.3 Comparison between downhole conductivity logs and the five types of conductivity estimates for bores HC9, HC10, HC11 and HC12.
Figure C.4 Comparison between downhole conductivity logs and the five types of conductivity estimates for bores CLPR36, CLPR47 and CLPR58.
Figure C.5 Scatter plot comparisons between conductivities measured by downhole conductivity logging and estimates from the five conductivity estimation algorithms.

Note: Each point represents the average conductivity over each 5 m depth interval intersected. The black diagonal line is not a line of best fit but the line of 1:1 correspondence along which the scatter points would ideally lie.