Monte Carlo Inversion of SkyTEM™ AEM data from Lake Thetis, Western Australia

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SUMMARY

A SkyTEM™ airborne electromagnetic dataset was inverted using a 1D reversible jump Markov chain Monte Carlo algorithm. The inversion of each dual-moment sounding generates an ensemble of 300,000 models that fit the data. The algorithm automatically varies the number of layers in the large range of models that are tested.

Analysis of the statistical properties of the ensemble yields a wealth of information on the probable conductivity distribution plus the mean, mode, median and most likely summary models. Robust information on the non-uniqueness and uncertainty of the results is also afforded by the ensemble. These are conveyed on conductivity map and section products. Estimates of the probable depths to interfaces are a further outcome. These depth estimates show great potential as an aid for mapping geological surfaces.

The resulting conductivity maps and sections are coherent and appear to be geologically realistic on face value. However it is demonstrated with 3D modelling that a plausible hydrogeological interpretation on the sections is likely to be an artefact of 1D inversion of a 3D geological scenario.

Key words: Electromagnetic, airborne, inversion, Monte Carlo, uncertainty, 3D.

INTRODUCTION

During 2011 Groundprobe Geophysics Pty Ltd flew a SkyTEM™ airborne electromagnetic (AEM) survey in the vicinity of Lake Thetis near Cervantes in Western Australia. The survey was commissioned by the Western Australian Department of Water as part of the Mid West Groundwater Dependent Ecosystem Vulnerability Project. Groundprobe Geophysics processed and then initially inverted the dataset using the iTEM fast approximate inversion (Christensen, 2005; Christensen and Tølbøll, 2009).

Subsequently the data were inverted using a reversible jump Markov chain Monte Carlo (rj-McMC) 1D inversion algorithm recently developed at Geoscience Australia.. In contrast to a deterministic inversion which results in a single final model, the rj-McMC program generates an ensemble of hundreds of thousands of models, all of which fit the data to within the noise levels. From the ensemble, various different conductivity models can subsequently be extracted, and its statistical properties yields a wealth of information about the non-uniqueness/uncertainty of the models. The utility of the method is demonstrated using the Lake Thetis dataset.

An important difficulty for the interpretation of 1D inversion results of the Lake Thetis dataset was the artefacts, at the edge of the ocean and salt lakes, which were due to the 1D inversion of the strongly 3D geology. A study using the MarcoAir 3D modelling code was able to generate artefacts very similar to those seen in the field data and verified that they were due to 3D responses at the edges of the highly-conductive lake.

MONTE CARLO INVERSION

The software program developed for 1D rj-McMC inversion of AEM data developed at Geoscience Australia. The methodology, previously described by Brodie and Sambridge (2012), was adapted from the 2D seismic tomography inversion work of Bodin and Sambridge (2009). Similar techniques in the geophysical literature include Malinverno (2002) and Minsley (2012).

The reversible jump (rj) feature of the algorithm means that the number of layers in the 1D models does not have to be fixed in advance. The inversion automatically explores a range of models with a different number of layers. It tends to favour models with the fewest number of layers that allow the data to be fitted, in essence providing a data-driven Occam's Razor.

The 22 high- and 24 super-low-moment Z-component data were inverted simultaneously. The inversion took into account the differing transmitter (Tx) and receiver (Rx) heights and orientations caused by the tilt of the Tx-Rx frame. In the inversion of each dual-moment AEM sounding an ensemble of 300,000 models were generated in a Markov Chain.

The algorithm is considerably more computationally expensive than deterministic inversions. However its advantage is that a wealth of information can be extracted from the ensemble. Figure 1 shows a summary of the information that may be gleaned from the inversion of one sample. Figure 1a shows the convergence profile of the

Markov chain. An acceptable data misfit (horizontal red line) was achieved well before the 10,000 sample burn-in period (vertical red line). Note that the data misfits are not normalized by the number of data, thus the number of data (46) represents an acceptable misfit.

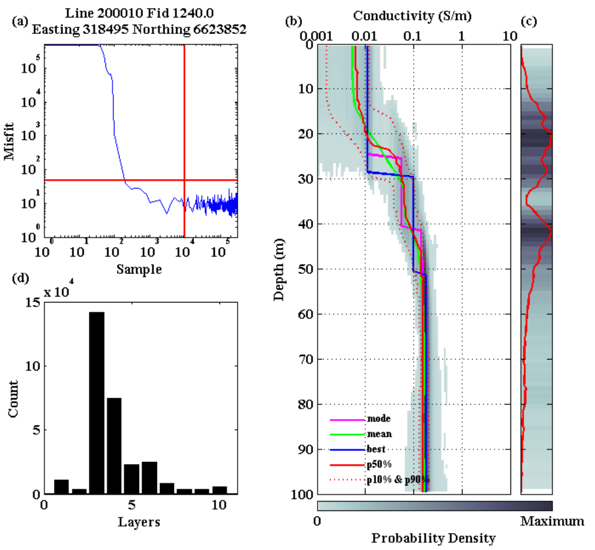

Figure 1. Summary plot of inversion results for one sounding showing (a) data misfit convergence, (b) the 2D PPD histogram, (c) the 1D change-point histogram, and (d) histogram of the number of layers.

The 290,000 models sampled after the burn-in period, all of which fit the data within the estimated noise envelope, are used to build up a 2D histogram of the posterior probability density function (PPD). The PPD is shown in Figure 1b as the grey shading, with darker areas being more probable. Then by slicing through the 2D PPD at different depth-bins (histogram rows) various statistics relating to the probable conductivity distribution at every depth can be extracted. Slices through the PPD in Figure 1b, at 10, 20 and 60 m depth, are shown in Figure 2. The mean, mode, most likely (best), 50% (median), 10th and 90th percentile summary models are all superimposed on Figure 1b.

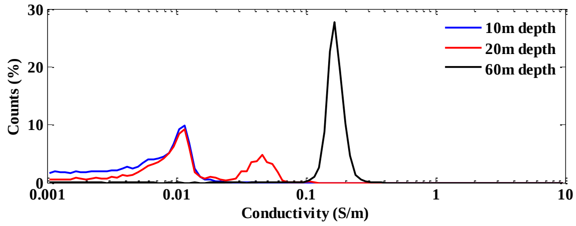

Figure 2. Slices through (rows of) the PPD histogram, shown on Figure 1b, at 10, 20 and 60 m depth.

The mean, mode, best and median summary models are all saved for every sounding. They are then compiled or stitched together, in the same fashion as for conventional inversions, into conductivity depth slice maps and sections. An example flight line multiplot containing conductivity sections for the four summary models plus the original iTEM inversion is shown in Figure 3.

Roughly speaking, the 10th and 90th percentile summary models represent the lower and upper limits of the probable conductivity range. The distance or spread between the 10th and 90th percentile models at any given depth can be interpreted as one measure of uncertainty or resolution of the conductivity at that depth. This information is conveyed on maps by making uncertain areas more transparent (e.g., Figure 3).

In the conductivity structure in Figure 2b the resolution at 60 m depth is superior (smaller spread) to that at 10 m depth. This may seem counter-intuitive, but it is because of two factors: (i) the AEM system is more sensitive to the conductors at 60 m than the resistors at 10 m, and (ii) most importantly we are viewing the results in terms of log-conductivity rather than straight linear-conductivity. The resolution would actually be better at 10 m if it were measured in terms of linear conductivity. Thus it is important to stipulate the measure of resolution accordingly.

Another output of the algorithm is a 1D change-point histogram shown in Figure 1c. This histogram provides information on the most frequent (probable) depths at which layer interfaces occur in the ensemble. In Figure 1c there are strong indications of a layer interfaces at around 22 and 42 m. The peaks in the change-point histogram can also be extracted and used to automatically interpret layer boundaries.

For example, the depth of the largest peak has been extracted and plotted as black dots on the conductivity sections on Figure 3. The line of dots gives a clear indication of a layer boundary and, with refinement to identify more peaks, has potential to form the basis of an automatic layer picking algorithm.

Finally, the number of layers required to explain the data can also be extracted from the ensemble. A histogram of the probable number of layers is shown in Figure 1d.

The algorithm's ability to identify sharp interfaces is a distinct advantage over multi-layer regularized (smooth-model) inversions that necessarily blur out interfaces. Likewise, its ability to change the number of layers is beneficial because it avoids the necessity to pre-suppose the number of layers, which is a common pitfall of conventional few-layer non-regularized inversions.

3D MODELLING

One feature of the 1D inversions from Lake Thetis is that the interface between the near-surface resistive and deeper conductive layers from the Monte Carlo inversions (indicated by the black dots on Figure 3) approaches the surface in the vicinity of the lake. A similar effect is seen in the iTEM inversions (lowest panel of Figure 3) where the deeper of the two conductive layers appears to bend upwards at the edges of the lake and connect with the conductive lake sediments. This poses the hydrogeological question of whether there is a potential connection between the hypersaline waters of the lake and the deeper conductive layer.

Examination of the horizontal (X-) component SkyTEM data from line 200050 showed that there were strong anomalies causing sign changes in the response at the eastern and western edges of the lake, at the points where the deep interface (or layer) approaches the surface. These X-component anomalies could not be correlated with changes in the attitude of the transmitter loop, and were thus taken to be indicative of three-dimensional effects in the data.

In order to investigate whether the conductor geometry near the lake was in fact real, a 3D model of the high-moment SkyTEM™ response was computed using MarcoAir v2.84 (Xiong et al., 2007) and then inverted using the 1D iTEM inversion. For comparison with the 3D results, a simple layered model was also computed and inverted using iTEM. Gaussian random noise was added to both the 3D and 1D model responses prior to inversion.

The layered model shown in the upper panel of Figure 4 was based on a conductivity log from a shallow borehole and is summarised in Table 1. The conductive fourth layer has been well-imaged by the iTEM inversion (top panel of Figure 4).

Layer	Conductivity (mS/m)	Thickness (m)
1	200	4
2	333	4
3	200	10
4	500	10
5	200	-

Table 1 Layered conductivity model derived from a borehole conductivity log at Lake Thetis.

The 3D model of Lake Thetis consisted of a prism of conductivity 3333 mS/m embedded in the same layered model in Table 1. The prism had an extent of 400 m in the flight line direction, 300 m perpendicular to the flight line and a thickness of 10 m. The top of the prism was at surface and it was centred beneath the flight line at a distance of 10000 m (Figure 4).

The 1D iTEM inversion of the 3D model data is shown in the lower panel of Figure 4. Away from the lake, the conductive fourth layer of the model has been well resolved. The conductivity and thickness of the lake sediments have also been well-recovered by the inversion near the centre of the lake (profile coordinate 10000). However, features emanate diagonally downwards from the edges of the lake and appear to connect with the deeper conductive layer at the left and right-hand ends of the profile. These features do not correspond to the geometry of the 3D input model and are thus artefacts. This shows that the apparent connection between the lake and the deeper conductor (or interface), shown in the Monte Carlo and iTEM sections in Figure 3, is a consequence of 1D inversion of 3D EM responses, and is unlikely to be a genuine hydrogeological feature.

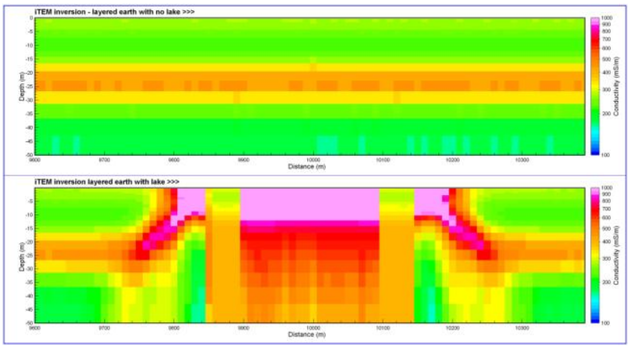

Figure 4. Comparison of a 1D iTEM inversions of synthetic data generated from a purely-layered model (top panel) and a 3D model including a conductive block representing conductive waters and sediments of Lake Thetis (lower panel).

CONCLUSIONS

The rj-McMC inversion algorithm was successfully used to generate 1D conductivity models from the Lake Thetis SkyTEM™ survey data. The algorithm provides a wealth of information from the inversion of every single sample. This includes the probable conductivity-depth distribution histogram, plus mean, model, median and most likely summary models.

Each class of summary model can be compiled into maps and sections in the conventional manner. Percentile statistics, gained from the histograms, can be used to convey uncertainty information on conductivity map and section products used by interpreters. Peaks from the changepoint histogram show great potential as a method for mapping the depth to geological interfaces. Conductivity sections generated from the rj-McMC results are coherent and have an appearance that is geologically plausible.

Nevertheless, the 1D inversion of data synthetically generated for a 3D conductivity mode1 demonstrated that some conductivity features shown on the sections may not be genuine. Importantly, the 3D modelling study highlights that a hydrogeological linkage between a hypersaline lake and deeper sediments, which could reasonably be interpreted from the 1D rj-McMC and iTEM inversions, may not actually exist.

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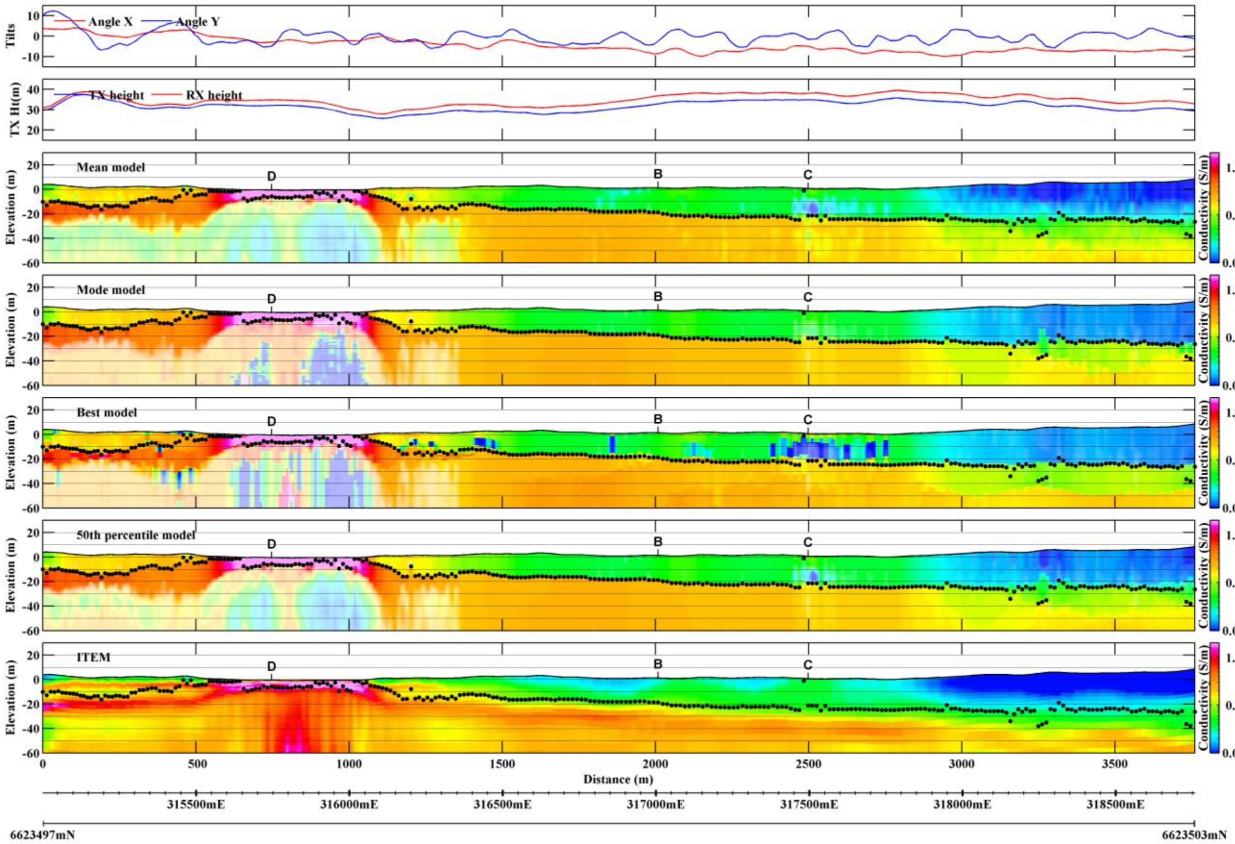

Figure 3. Multiplot for flight line 200050. The panels from top to bottom show the (i) frame tilts, (ii) TX and RX height, (iii) conductivity section of mean models, (iv) conductivity section of mode models, (v) conductivity section of median models, (vi conductivity section of most probable models, and (vii) conductivity section of the separately derived ITEM inversion results.