CSIRO PUBLISHING

Exploration Geophysics
http://dx.doi.org/10.1071/EG14015

Response to comments by Adam Smiarowski and Shane Mulè on: Christensen, N., and Lawrie, K., 2012. Resolution analyses for selecting an appropriate airborne electromagnetic (AEM) system, *Exploration Geophysics*, 43, 213–227

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Received 6 February 2014, accepted 1 May 2014, published online 3 June 2014

First of all, we would like to express our appreciation for the thorough Comment by Adam Smiarowski and Shane Mulè, CGG, challenging some of our methods of analysis and conclusion in our paper: Christensen, N., and Lawrie, K., 2012. Resolution analyses for selecting an appropriate airborne electromagnetic (AEM) system, *Exploration Geophysics*, 43, 213–227.

It is always productive with a Comment as sharp as this one, as it gives us an opportunity to catch up on what was neglected in the paper and to modify and expand on our conclusions in the light of the just objections of the Comment; we also have greater freedom to discuss project methodologies now that the project reports have been released (Lawrie et al., 2012*a–e*).

The Broken Hill Managed Aquifer Recharge (BHMAR) project was commissioned by the Australian Government in response to an election commitment after nearly 10 years of drought across the Murray-Darling Basin. This was the single largest groundwater project commissioned by the Australian Government in the past 30 years, and with community water supplies at stake, short time frames for data acquisition and assessment, and considerable investment in water infrastructure being considered, the client required a very high degree of confidence in project inputs and results. With a lack of AEM data in a similar hydrogeological setting, the standard Geoscience Australia (GA) method of assessing the ability of candidate systems (derivative analysis) to map defined targets was initially used to narrow the field of candidate systems. However, the analysis was considered incomplete (Lawrie et al., 2009*a*), and did not provide the required certainty in the ability of the short-listed systems to map the known ground targets (Lawrie et al., 2009*b*). To try and resolve this issue, the derivative analysis approach was supplemented by an inversion analysis approach (Lawrie et al., 2009*b*). While the latter approach provided greater insights into some of the potential resolution capabilities between the TEMPEST and SkyTEM systems, neither analysis method provided sufficient confidence in the ability of any of these systems to detect and resolve the known targets. For this reason, a decision was made to acquire test line data over selected targets with the SkyTEM and TEMPEST systems.

The main body of our reply relates to the theoretical analyses that are the main focus of the Comment. However, we also find it important to call attention to the context in which they were used. Ultimately, the decision to select one particular system was made only after acquiring data for two test lines over known targets in the project area (Lawrie et al., 2012*a*).

Noise model

The BHMAR project data were acquired in 2009, and the project was completed at the end of 2013. Project reports (Lawrie et al., 2012*a–e*) are now freely available on the GA website.

With regard to the theoretical analysis approaches, we explained in our paper that GA obtains noise estimates from the contractors involved in their surveys and keeps them for reference and use in future analyses. Additionally, GA estimates noise characteristics from repeat line data and high altitude measurements, independent of the contractor, and before undertaking the comparative analysis, we made sure that the noise models were current. It appears that Smiarowski and Mul‘e do not have any objections to the actual numbers of the noise model we used for the analyses of z-component data and that we therefore stand on common ground for the discussion of the effect of including the x-component in the analysis.

Measuring geometrical system configuration parameters

It is good that CGG has developed the TEMPEST system to monitor some of the geometrical configuration parameters that were not measured before; these were not available at the time of selecting the system for the BHMAR study. We are sure that interpreters of TEMPEST data will appreciate this improvement. These measurements are of great importance, especially for a configuration with a trailing bird where the configuration geometry varies continually. It is of particular importance to monitor the bird pitch and roll, if x-component data are to be included in the inversion, and we can only encourage CGG to continue their work with monitoring this parameter. At the time of writing our manuscript, however, system parameters were not so systematically measured as they apparently are now, so obviously some of our conclusions in the paper concerning the effects of varying system geometry will have to be modified.

The importance of measuring the geometrical parameters for systems with varying geometry lies in the fact that they have a considerable influence on the measured data and they will have to be included in the inversion. Not all interpreters of TEMPEST data do so, but, fortunately, serious interpreters have adopted this practice. The effect of including more parameters in the model space is of course that, overall, the earth parameters are more poorly resolved than if these parameters were known. The theoretically consistent way of including the independent measurements of the geometrical parameters is to still include the parameter in the model space, but add the measured values as prior information with a proper uncertainty. The improvement in resolution obtained from including the prior information is eventually determined by its uncertainty and the degree of consistency between the measured geometrical parameters and the EM data.

The SkyTEM system, having a rigid construction, is characterised—besides the survey height of system—by only two geometrical parameters: the pitch and the roll of the system as a whole. Both transmitter height and the two angles are measured with dual systems during flight; this was done from the introduction of the system.

We do not quite agree that the TEMPEST system should be included among the systems with ‘well-defined geometry’ since the receiver position does in fact vary constantly, but it is an important improvement that the system can be included among the systems with ‘well-monitored geometry’.

Calibration

As with any other contractor, CGG has performed a comprehensive test and calibration of the system, and it was never our intention to suggest otherwise. Rereading our paper, we see that we have used the words ‘calibration’ in a somewhat looser sense than we probably should have, and that confusion may have arisen from that. By ‘calibration’ we also alluded to the varying—and at that point in time unmeasured—geometrical parameters and the negative effect they would have on the system resolution. We apologise for any confusion that might have arisen from these statements.

The inclusion of in-line component data

In our paper, we chose to perform the comparative analyses based on *z*-component data alone. However, we appreciate that the *x*-component most often forms an integral part of the data set used in various forms of inversion of TEMPEST data. Consequently, analyses where the *x*-component is included are quite relevant for the TEMPEST system, and Smiarowski and Mulè’s Comment gives us an opportunity to extend our analyses.

We have repeated the analyses of Smiarowski and Mulè with the noise estimates they reported, i.e. we have the same noise level for the *z*-component as in our paper, and the bias and additive noise contributions for the *x*-component are 1.9 times those of the *z*-component. We have kept the multiplicative noise figure of 1.7% for both components. The results can be seen in Figures 1 and 2. With small and insignificant differences, we fortunately get more or less the same results as Smiarowski and Mulè.

Figures 1 and 2 show colour-coded templates of the relative standard deviation of all model parameters, resistivities and thicknesses, as a function of the resistivity of the second layer varying from 1 to 10 Ωm on the abscissa and the resistivity of the third layer varying from 0.5 to 50 Ωm on the ordinate. Parameters with a small relative standard deviation are shown in red to orange colours and parameters with a large relative standard deviation are shown in green to blue colours.

For the TEMPEST system, the effect of including the *x*-component in the analyses is most striking for the resistivity of the top layer which is now determined with smaller uncertainty than before. There is some improvement on the resolution of the resistivity of the third layer and a clear improvement on the resistivity of the fifth layer, the bottom layer. There is no improvement on the resolution of any of the layer thicknesses which are all still unresolved.

To permit a comparison, we did the same exercise with the SkyTEM system including the *x*-component of the data in the analyses. After consulting with SkyTEM (personal communication with Nicklas Nyboe) we settled on noise estimates for the *x*-component that were two times the estimates for the *z*-component for the additive noise. As explained in our paper, bias can be neglected for the SkyTEM system, and we have kept the multiplicative noise at a value of 1.5%, which is the same as before.

For the SkyTEM system, the effect of including the *x*-component is that there is improvement in the resolution of the top layer (cannot really be seen in Figure 1 because it is already very well determined), there is some improvement in the resolution of the resistivity of the second layer, a very slight improvement concerning the resistivity of the third layer and essentially no improvement on the resistivities of the fourth and fifth layers. Most striking is a clear improvement in the resolution of the thickness of the top layer. There is a slight improvement on the thickness of the second and third layers, but essentially no improvement for the thickness of the fourth layer.

As pointed out in Smiarowski and Mulè’s Comment, the offset geometry of the TEMPEST system means that, over a fairly wide interval of delay times, the *x*-component is of the same order of magnitude as the *z*-component and thereby has a reasonable signal-to-noise ratio that warrants its inclusion in an inversion. The SkyTEM system is not quite a central loop system – there is a distance between the centre of the transmitter loop and the receiver coils of ~10 m, so for increasing delay times, the *x*-component measured by the SkyTEM system quickly becomes smaller than the *z*-component, and it will therefore obtain an inferior signal-to-noise ratio compared with the *z*-component. These observations are illustrated in Figure 3.

An immediate qualitative estimate is therefore that the relative improvement obtained by including the *x*-component is more pronounced for the TEMPEST system than for the SkyTEM system. To quantify this expectation, we have compared the posterior variances before and after including the *x*-component for both systems for all model parameters of the analyses and the result is given in Table 1. The table gives the average over the 421 models of the analyses of two different measures:

$$\Delta R = \frac{1}{421} \cdot \sum_{i=1}^{421} \left(\frac{1}{\operatorname{var} p_{xz}} - \frac{1}{\operatorname{var} p_z} \right) \tag{1}$$

$$\Delta Q = \frac{1}{421} \cdot \sum_{i=1}^{421} \frac{(\operatorname{var} p_z - \operatorname{var} p_{xz})}{\operatorname{var} p_z} \tag{2}$$

where var p_{xz} and var p_z are the variances when including both components and only the *z*-component, respectively. The higher the value of ΔR, the more improvement in the resolution by including the *x*-component. This measure highlights the situation where an improvement has resulted in a low variance. The ΔQ measure gives the relative improvement in variance.

Table 1 shows that the relative improvement in resolution, ΔQ, is consistently higher for the TEMPEST system than for the SkyTEM system: it is relatively more important to include the *x*-component for the TEMPEST system. Except for the resistivity of the fifth layer, the ΔR measure is consistently higher for the SkyTEM system than for the TEMPEST system, illustrating what is already demonstrated in our paper that for most parameters, the SkyTEM system has the better resolution.

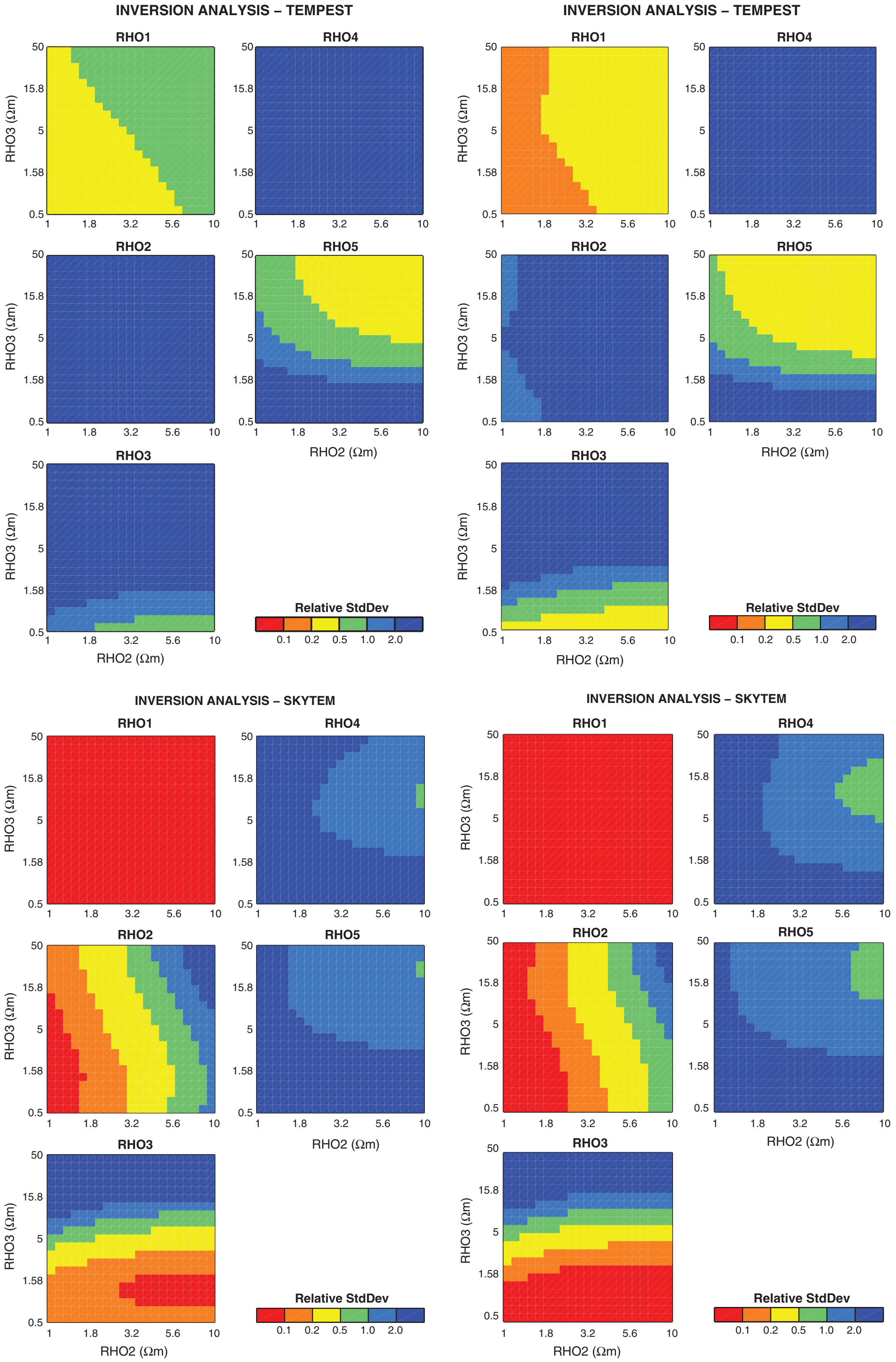

Fig. 1. Top row: Analysis templates for the layer resistivities for the TEMPEST system before (left) and after (right) including x-component data in the analyses. Bottom row: Equivalent templates for the SkyTEM system.

To a certain extent, the result surprised us somewhat. We had expected a smaller improvement for the SkyTEM system than that seen in Table 1.

Looking at the end results of including the x-component rather than the relative improvement, it is clear that the TEMPEST system has a better resolution than the SkyTEM

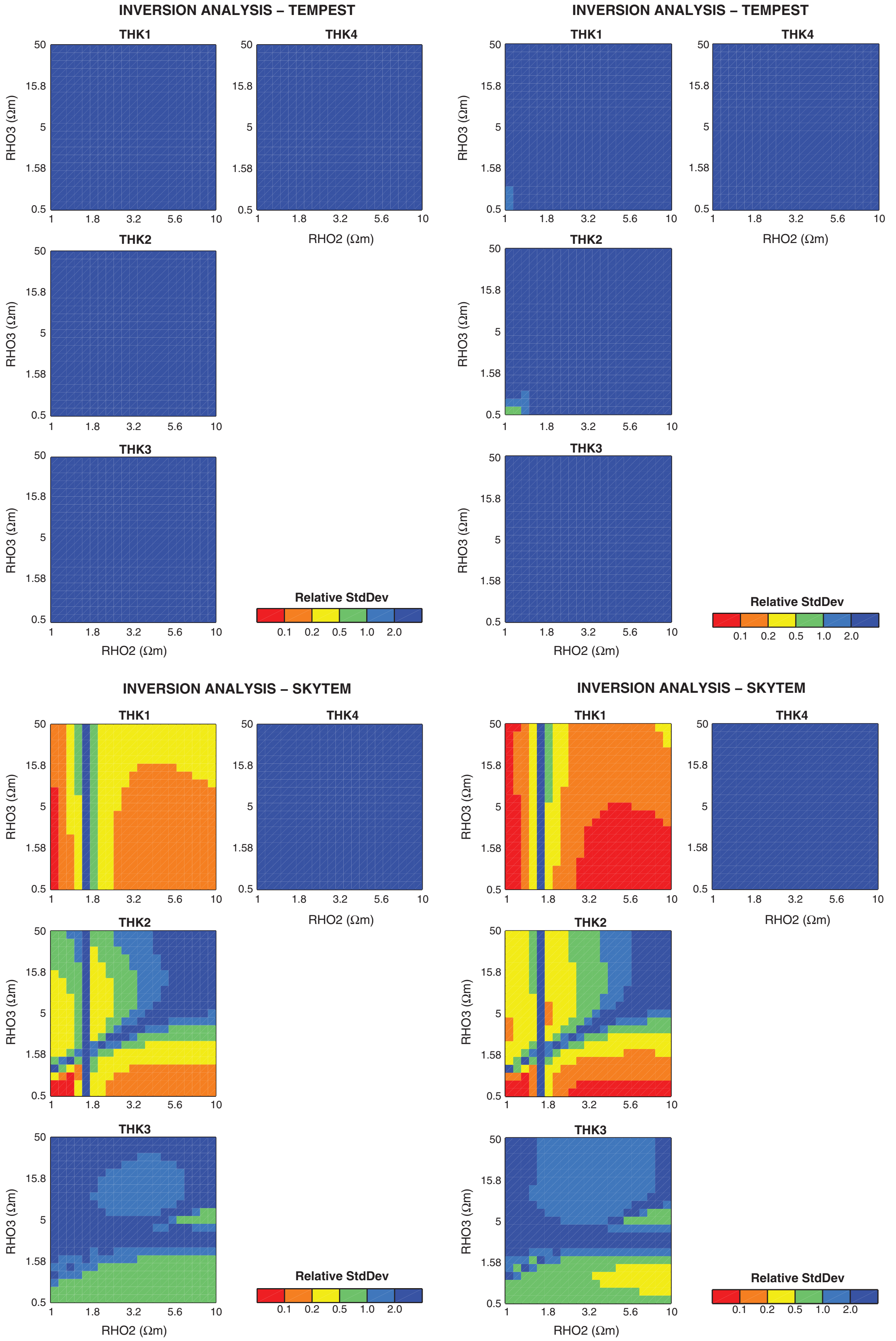

Fig. 2. Top row: Analysis templates for the layer thicknesses for the TEMPEST system before (left) and after (right) including x-component data in the analyses. Bottom row: Equivalent templates for the SkyTEM system.

system of the resistivity of the fifth layer, the bottom layer. This was true also before the x-component was included in the analysis as we pointed out in our paper, but now it is even clearer. Apart from the resistivity of the bottom layer, all other parameters are better determined by the SkyTEM system, even when including the x-component

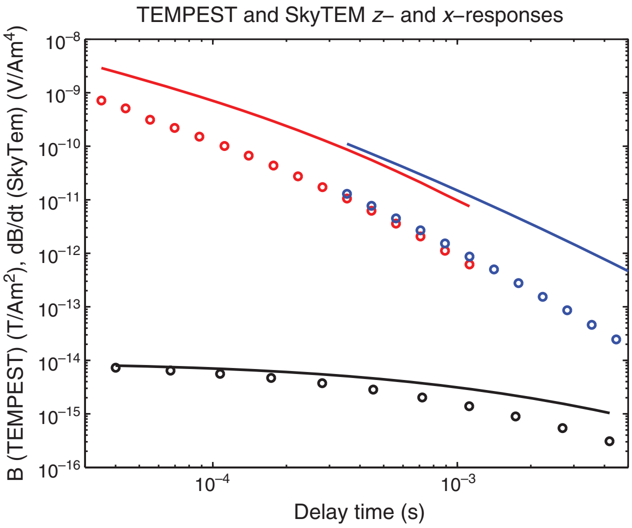

Fig. 3. TEMPEST and SkyTEM *z*- and *x*-responses for a half-space with resistivity 5 Ωm. Full drawn curves are *z*-responses while open circles indicate *x*-responses. Black is TEMPEST, red is SkyTEM Low Moment and blue is SkyTEM High Moment.

Table 1. Comparison using equations 1 and 2 of the improvement in resolution of the layer resistivities, ρ_1-ρ_5, and thicknesses, t_1-t_4, by including *x*-data in the analyses for the TEMPEST and SkyTEM systems.

Parameter/system	ΔR TEMPEST	ΔR SkyTEM	ΔQ TEMPEST	ΔQ SkyTEM
ρ_1	19.055	7586.400	0.926	0.886
ρ_2	0.074	42.386	0.940	0.755
ρ_3	0.892	47.194	0.927	0.739
ρ_4	0.024	0.121	0.883	0.591
ρ_5	2.554	0.075	0.727	0.567
t_1	0.058	41.332	0.918	0.751
t_2	0.034	12.738	0.876	0.737
t_3	0.012	0.357	0.902	0.637
t_4	0.004	0.013	0.826	0.584

in the TEMPEST system, but leaving it out for the SkyTEM system.

In our paper, in the section concerning the results of the analyses, we did in fact explicitly state that the TEMPEST system has a superior resolution of the resistivity of the fifth model layer. Upon reading the discussion section, we see that this was not mentioned there, for which we apologise.

As mentioned in the previous section, the *x*-component is very sensitive to the pitch angle of the receiver because it is contaminated with the product of the *z*-response and the sine of the pitch angle. This is an important issue for both the SkyTEM and the TEMPEST systems. The usefulness of the *x*-component therefore depends critically on the accuracy with which the receiver tilt angles are known. This is the reason why it is necessary when including *x*-data to also include the receiver tilt angles as inversion parameters – which in turn emphasises the importance of measuring these as accurately as possible. The *x*-component data of the SkyTEM system are more prone to tilt errors than those of the TEMPEST system because, for the SkyTEM system, the *z*-component is much larger than the *x*-component, while for the TEMPEST system, they are of the same magnitude. However, the tilt angles are well measured with the SkyTEM system while this is not the case (yet?) for the TEMPEST system.

Kirkegaard et al. (2012) studied this problem and performed an analysis of how much improvement could be achieved by including the *x*-component in 1D inversion of SkyTEM data and found that it often creates more problems than it solves. For 1D inversion, current practice with SkyTEM data is not to use the *x*-component data because the improvements in resolution are deemed to not quite justify the efforts involved in processing an extra data component. The *x*-component is more prone to coupling to man-made good conductors in inhabited areas and the coupled data sets must be removed more or less manually, and the *x*-component is more sensitive to lateral changes in conductivity than the *z*-component and thereby becomes inconsistent with a 1D approach to inversion (Ley-Cooper et al., 2010). The same considerations are of course also valid for the TEMPEST system, but because of its larger survey height and the larger lateral extent of the sensitivity of the system, coupling is relatively weaker (and not as visible) and the system averages over larger earth volumes, giving rise to a more ‘well-behaved’ *x*-component.

Discussion and conclusions

Overall, the measurement of geometrical parameters for the TEMPEST system will improve the resolution capabilities of the system, and consequently our conclusions about the TEMPEST system relating to the varying geometry of the system will have to be modified towards more positive conclusions, recognising that these improvements occurred subsequent to acquisition of the BHMAR data, and submission of our initial manuscript. It is, however, beyond the scope of this reply to quantify the improvement.

Obviously, including the *x*-component in the inversion improves the resolution for both the TEMPEST and the SkyTEM systems. The relative improvement is larger for the TEMPEST system than it is for the SkyTEM system, and the improvement highlights the fact that the TEMPEST system resolves the resistivity of the fifth layer, the bottom layer, of the analysed models better than the SkyTEM system. Apart from this parameter, the resolution of the SkyTEM system is better than that of the TEMPEST system for the analysed models; this is also true when the *x*-component data are not included in the SkyTEM analyses.

The *x*-component data are generally used more often in 1D inversion of TEMPEST data than is the case for the SkyTEM system. Although we have not pursued a comprehensive study, we would expect that the potential problem of inconsistency between *z*- and *x*-component data is smaller for the TEMPEST system than for the SkyTEM system because of the larger averaging volumes of the TEMPEST system.

Although including the *x*-component in the inversion of SkyTEM data does improve the resolution, the additional effort of processing the more noisy and coupling-influenced *x*-component is most often deemed to be not worth it in terms of the actual improvement in resolution. This situation is likely to change when 3D inversion becomes the preferred (and feasible) inversion option for AEM data.

However, as mentioned earlier, and in our initial paper, the inversion analyses presented in that paper and now extended in this reply were ultimately only one part of the AEM system selection process for the BHMAR project. Both derivative and inversion analyses are, by their nature, theoretical, and it is impossible, in a theoretical analysis, to capture all of the aspects relevant for real surveys with little margin for error in practical time frames. In reality, neither the derivative nor inversion analysis provided the degree of certainty required (by the project manager and client) to ascertain whether any of the candidate AEM systems were able to map the key managed aquifer recharge targets recognised in the study area. Consequently, a decision was made to acquire data over a test line with the two systems (SkyTEM and TEMPEST) that performed best in the derivative and inversion analysis studies.

This approach was vindicated with quite distinctive performances observed between these two systems, especially when compared with borehole and ground geophysical and hydrogeological data over known targets. Data were inverted both with contractors' software and with reference software common to all systems and the results were compared. Ultimately, it was the test lines, particularly in the near-surface (top 20 m), that made the SkyTEM system stand out as the best system for the particular targets in the project area. SkyTEM mapped the key multi-layered hydrostratigraphy and water quality variability in the key aquifer that defined the key MAR targets, although the TEMPEST system had a superior performance at depths exceeding 100 m. Importantly, the SkyTEM system also mapped numerous, subtle fault offsets in the shallow near-surface. These structures were critical to mapping recharge and inter-aquifer leakage pathways. Further analysis has demonstrated that selection of the most appropriate AEM system and inversion can result in order of magnitude differences in estimates of potential groundwater resources.

The acquisition of SkyTEM data was an outstanding success, demonstrating the capability of AEM systems to provide high-resolution data for the rapid mapping and assessment of groundwater and strategic aquifer storages in Australia's complex and highly salinized floodplain environments. The SkyTEM data were used successfully to identify 14 major new groundwater targets and multiple MAR targets, and these have been validated by an extensive drilling program (Lawrie et al., 2012*a*–*e*).

Increasingly, the demand from clients for higher certainty in project decision-making, and quantifying errors, will see development of new system comparison analytical approaches such as the inversion analysis approach documented in our initial paper. Ultimately, system fly-offs are likely in high-profile projects where budgets permit.

Acknowledgements

We thank Ross Brodie, Anders Vest Christiansen and Andrea Viezzoli for sharing with us their practical experience with inversion of TEMPEST data. Nicklas Nyboe, SkyTEM, is thanked for providing the estimates of the noise factors pertaining to the *x*-component of the SkyTEM system.

References

Kirkegaard, C., Foged, N., Auken, E., Christiansen, A. V., and Sørensen, K. I., On the value of including x-component data in 1D modeling of electromagnetic data from helicopterborne time domain systems in horizontally layered environments: *Journal of Applied Geophysics*, 2012, **84**, 64–69.

Lawrie, K. C., Munday, T., Clarke, J. D. A., Fitzpatrick, A., Cullen, K., Apps, H. E., Brodie R. S., Ransley, T., Cahill, K., Lane, R., Richardson, M., English, P., and Hatch, M., 2009*a*, Broken Hill Managed Aquifer Recharge Project, Phase 1: Final Report. Geoscience Australia Professional Opinion 2009/03, p. 173.

Lawrie, K. C., Brodie, R. C., Gibson, D., Kuske, T. J., Halas, L., Tan, K. P., Cullen, K., Brodie R. S., Hannah, A., and Richardson, M., 2009*b*, Broken Hill Managed Aquifer Recharge Project, Phase 1: Report on AEM System Selection. Geoscience Australia Professional Opinion 2009/17, p. 147. Four Appendices.

Lawrie, K. C., Brodie, R. S., Tan, K. P., Gibson, D., Magee, J., Clarke, J. D. A., Halas, L., Gow, L, Somerville, P., Apps, H. E., Christensen, N. B., Brodie, R. C., Abraham, J., Smith, M., Page, D., Dillon, P., Vanderzalm, J., Miotlinski, K., Hostetler, S., Davis, A., Ley-Cooper, A. Y., Schoning, G., Barry, K., and Levett, K., 2012*a*, BHMAR Project: Data acquisition, processing, analysis and interpretation methods. Geoscience Australia Record 2012/11. Geocat 73819.

Lawrie, K. C., Brodie, R. S., Tan, K. P., Gibson, D., Magee, J., Clarke, J. D. A., Halas, L., Gow, L., Somerville, P., Apps, H. E., Smith, M., Christensen, N. B., Abraham, J., Hostetler, S., and Brodie, R.C., 2012*b*, BHMAR Project: Geological and hydrogeological framework and conceptual model. Geoscience Australia Record 2012/12. Geocat 73820.

Lawrie, K. C., Brodie, R. S., Dillon, P., Tan, K. P., Gibson, D., Magee, J., Clarke, J. D. A., Somerville, P., Gow, L., Halas, L., Apps, H. E., Page, D., Vanderzalm, J., Abraham, J., Hostetler, S., Christensen, N. B., Miotlinski, K., Brodie, R.C., Smith, M., Schoning, G., Barry, K., and Levett, K., 2012*c*, BHMAR Project: Assessment of conjunctive water supply options involving managed aquifer recharge options at Menindee Lakes. Geoscience Australia Record 2012/13. Geocat 73821.

Lawrie, K. C., Brodie, R. S., Tan, K. P., Somerville, P., Gibson, D., Magee, J., Clarke, J. D. A., Abraham, J., Gow, L., Halas, L., Apps, H. E., Hostetler, S., Christensen, N. B., Smith, M., Brodie, R. C., and Schoning, G., 2012*d*, BHMAR Project: Assessment of potential groundwater resources and underground storage options in the Darling Floodplain. Geoscience Australia Record 2012/14. Geocat 73822.

Lawrie, K. C., Brodie, R. S., Dillon, P., Tan, K. P., Gibson, D., Magee, J., Clarke, J. D. A., Somerville, P., Gow, L., Halas, L., Apps, H. E., Page, D., Vanderzalm, J., Abraham, J., Hostetler, S., Christensen, N. B., Miotlinski, K., Brodie, R. C., Smith, M., Schoning, G., Barry, K., and Levett, K., 2012*e*, BHMAR Project: Securing Broken Hill's Water Supply: Assessment of conjunctive water supply options involving managed aquifer recharge and/or groundwater extraction at Menindee Lakes–Summary Report. Geoscience Australia Record 2012/16. Geocat 73823.

Ley-Cooper, A. Y., Macnae, J., and Viezzoli, A., 2010, Breaks in lithology: Interpretation problems when handling 2D structures with a 1D approximation: *Geophysics*, **75**, 179–188.