TEMConfigurator, a new transient electromagnetic forward modelling interface, and evaluation of AgTEM-Wallaby and AgTEM-Wallaroo towed Transient Electromagnetic Systems capabilities and limitations.

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SUMMARY

Towed transient electromagnetic systems Wallaby and Wallaroo, operated with AgTEM and TerraTEM electronics have been in development and use in Australian agricultural and mining applications since 2002.

During development, many variations of towed transient electromagnetic survey have been attempted demonstrating that design must be limited within a small range of each of the relevant design parameters. One cannot, for instance, expect deeper penetration just from infinitely increasing any parameter. All parameters make a difference, but are optimal only in small ranges, and most must be measured and stabilized accurately. Forward modelling involving variation of all parameters is invaluable for recognising and teaching system limitations.

Forward modelling to generate sets of type curves provides a means of fully understanding capability and practicality of different towed TEM systems. New software, 'TEMConfigurator', developed by the principal author, facilitates generation of sets of type curves comparing any configuration over a range of earth models. It is an interactive graphical wrapper for only the time domain electromagnetic forward modelling capabilities of the program 'AarhusInv' of the Aarhus Hydrogeophysics Group.

For towed TEM systems, tests at sites of known geology have demonstrated that subtraction of forward modelled data from field data collected at a site of known response is essential for determining system response and for realising the full capability.

In-loop receivers detect the deep signal just as effectively as receivers out of the transmitter loop however accurate modelling of such signal is more difficult for in-loop receivers and must be balanced with consideration of logistical pragmatics.

The contrast between slightly different forward models should be evaluated to determine detectability of predicted features of interest in the ground prior to attempting any survey. TEMConfigurator facilitates such detectability prediction.

Key words: transient electromagnetic, towed TEM, AgTEM, Wallaby, TEM Configurator

INTRODUCTION

The Wallaby™ and Wallaroo™ transient electromagnetic (TEM) antennae systems have been gradually developed and utilized by the authors since 2002. The Aarhus PATEM (Auken & Sorensen, 2003) and Zonge NanoTEM (Barrett, 2003) towed TEM systems predate AgTEM, while the EMIT Loupe (Street et. al., 2018) and TEM Company tTEM (Auken, Foged, et. al., 2015) systems now also are in the market.

Niches of towed TEM

Towed TEM systems fill a niche in the geophysical imaging market where high-productivity, spatially-dense survey of bulk earth electrical conductivity (or its inverse, resistivity) is sought to many tens of metres deep beneath open farmland, open shallow water, and other navigable terrain. These systems overlap the niches of frequency domain bulk soil conductivity meters, hand laid TEM loop survey, and airborne EM survey.

Other niches filled by towed TEM are low deployment cost regional shallow groundwater survey and subcrop mapping, which can be extremely useful for constraining and focusing interpretation of certain types of geochemical sampling. At mining sites, towed TEM can resolve detailed variations pertinent to blast pattern design, ore selection, and slope stability risk. Towed TEM systems can have particular advantage in ground moisture pollution monitoring and remediation sites, which typically are cluttered with metallic 'cultural effects'. Due to the small ground surface footprint of towed TEM systems, particularly those with receiver loops within, or overlapping, the transmitter loops, decipherable signals can be rendered from groundwater pollution plumes amongst the inductive responses of surface metal features.

Interpreting towed TEM data

Because towed TEM responds principally to bulk earth electrical conductivity in the shallowest few tens of metres of ground, it is almost always mapping ground moisture related properties in some way or other. Salinity of moisture is perhaps typically the dominant property mapped. This typically is strongly related to clay distribution so towed TEM is a good means of mapping sediment texture and rock weathering profiles. In suitably detailed towed TEM survey, geological structures are typically mapped by their influence on weathering down faults and other preferential groundwater pathways. Alluvial depth and aquifer mapping is often possible but it can be difficult to interpret where resistive, fresh water filled sand and gravel fails to contrast well with unweathered rock.

Although we demonstrate here that towed TEM is suitable for detecting well beyond 100m deep, resolution is courser at greater depths so it is typically the case that thin deep aquifers within otherwise clayey strata cannot be detected. In contrast, the common scenario where potable groundwater is sought from gravel palaeovalleys cut into weathered strata laid down in marine environments, is suitable for towed TEM exploration even at depths approaching 200m deep. Exploration at such depth does however require extra care and effort, without which, modelling will simply confuse shallow features and system response with deep response. Using the new tool we have created, 'TEMConfigurator', it is possible to evaluate the sensitivity of configurations to both earth and equipment parameter variations.

WALLABY & WALLAROO PRACTICAL DESIGN

Wallaby

Figure 1 presents the Wallaby towed TEM antennae platform. This platform is designed to be towed by a 4WD quadbike, ATV, or a highway registered 4WD. When towed by large vehicles it must use the long drawbar as shown to reduce inductive coupling with the vehicle, however, for use with a quadbike, a much smaller drawbar can be used.

Wallaby can be used in Slingram mode, with a receiver loop gimble mounted on a pair of suspended telescopic booms protruding forward high above the ground in front of the towing vehicle where it can be manoeuvred with great agility. This provides received signal without problematic mutual inductance coupling with the transmitter loop but the practicality cost of adding this loop is considerable. It is used typically only for verifying the performance of the receiver loop shown in blue in figure 1. This offset receiver loop is designed to effectively null couple with the transmitter loop in a manner not sensitive to typical loop movement while keeping the platform weight and dimensions practical. Notes on figure 1 explain how nulling stability is achieved.

The side booms on Wallaby are elastically held forward and can be remotely retracted via rigging for passing traffic, gates, or gaps in vegetation. Impacts with vegetation are absorbed, occasionally with parts being torn off at designed, weak, readily replaceable links.

The patented structure of Wallaby is designed to directly transfer all impacts back to the tow ball of the towing vehicle sufficiently to stall the towing vehicle, and to glance off or ride over obstacles. Wheels are of maximum practical diameter to reduce roughness of travel and are solid or filled with cured foam for durability while suspension is up above the undercarriage.

The 220kg Wallaby structure can all be packed up telescopically into an aircraft unit load device for freight but to facilitate quick deployment it is typically only partially folded up and rolled onto a custom-made float trailer for transport between job sites.

Wallaroo

Figure 2 presents the Wallaroo towed TEM antennae platform in a configuration involving single person walked operation with assistance from an electric tractor. The person walks where they want to go and the tractor moves with them. In contrast with the 220kg Wallaby, Wallaroo was initially designed as a 12kg walked platform, so it does not have the durability of Wallaby.

The patented minimal Wallaroo structure involves just a longitudinal boom, upright post, and side booms and can be carried by two persons. Like for Wallaby, the side booms are elastically held, by rubber tendons, into sockets so they can be lifted by the operators via rigging so the system can pass through an 800mm wide gap.

Wallaroo has a 5.625m^2/turn receiver loop concentrically located within the 27.8m^2/turn transmitter loop at half boom width. By keeping loop sizes large it is feasible for this loop to operate even within the transmitter loop where mutual inductance is considerable. A high dynamic range receiver and robust preamplification/signal conditioning are necessary for working with the high mutual inductance. The concentric receiver loop is ideal for surveys requiring a small footprint survey for dense spatial detail or for where project specifications do not demand a considerable range of depth of investigation.

For projects requiring deep investigation, the Wallaroo platform should have a separate Slingram receiver loop added. In figure 2 a 6m^2 per turn loop is cantilevered in front of the electric tractor and stabilized by the walking operator. This loop will achieve typically double or more of the exploration depth of the concentric receiver loop with default pre-amplification. For fully walked operation, without the tractor, it is recommended that this loop be carried by a third person. Although walked Slingram Wallaroo survey is labour intensive and comparatively slow, the loop moment achieved, exceptional movement stability, and low mutual inductance can result in highest possible quality of data being collected even within the most difficult of open terrain.

The entire Wallaroo system, including the tractor, when rapidly packed, fits onto the tray and ladder rack of a dual cab ute.

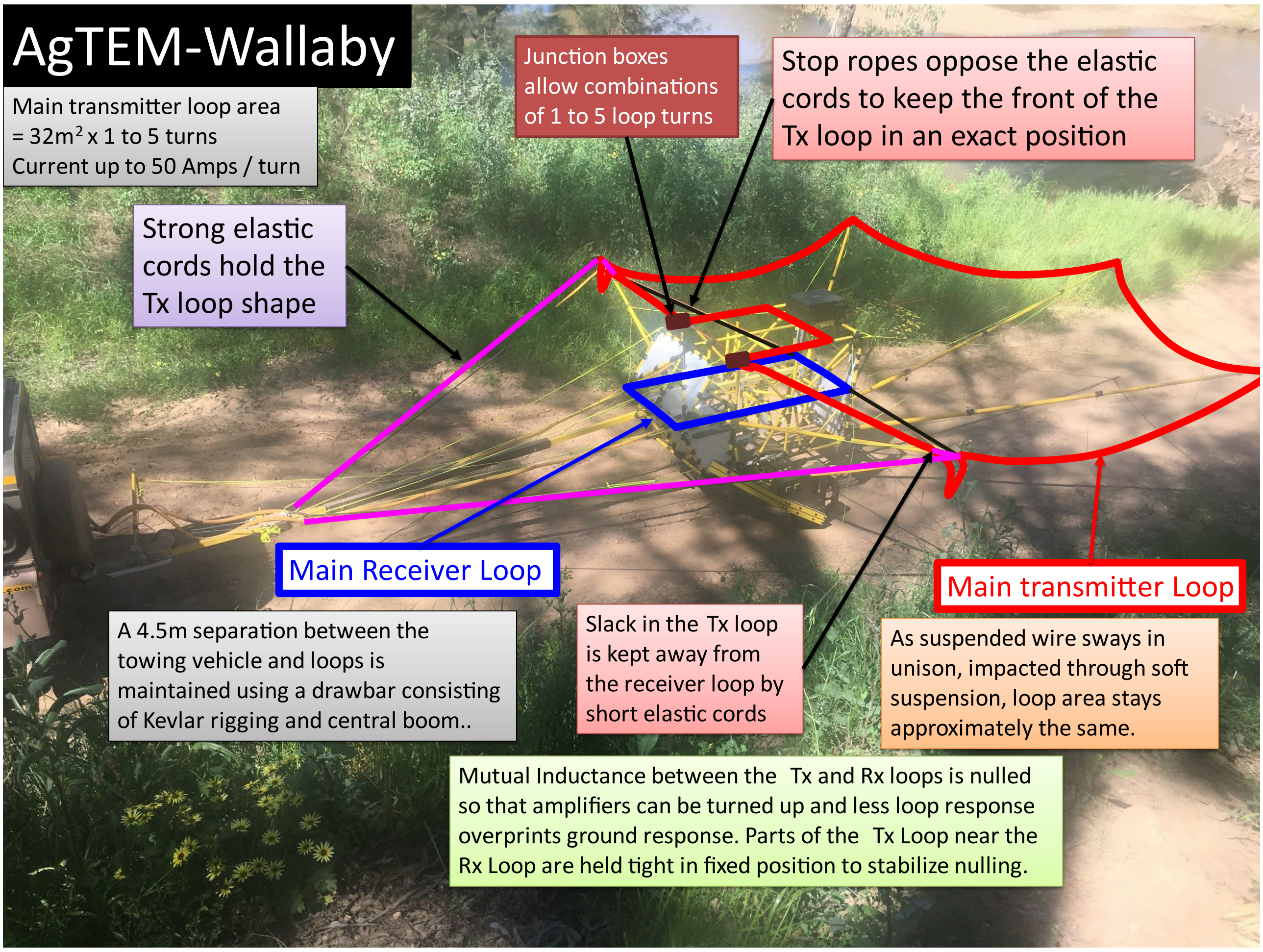


Figure 1. The key parts of the Wallaby towed transient electromagnetic antennae system. The Wallaby system is designed for efficient long-duration surveys across cleared agricultural land.

Figure 2. The Wallaroo transient electromagnetic antennae system. The Wallaroo antennae may either be walked by three persons (without the support structures and electric tractor shown) or propelled by the tractor guided by one person as shown. The walking person guides a frame with steering and speed controls plus sensors that detect their movement so that it moves where they walk. Weight bearing on the operator is largely supported by a cantilever arrangement so the weight on the operator is close to neutral when torque is not applied by the tractor. Walking 20km per day with Wallaroo is practical.

A FORGOTTEN EDUCATIONAL TOOL – FORWARD MODELLING AND TYPE CURVES

To fully evaluate towed TEM systems, comprehensive electromagnetic understanding is necessary. Before computational efficiency and abundant cheap computer memory provided us the opportunity to create 'black-box' type automated modelling computer packages, practitioners of geophysics used to learn the significance of data being collected by reference to type curves. These were first made using scaled down physical models, and later, by laborious manual mathematical calculations. The value of knowledge of such type curves seems to have been forgotten, and modern EM survey practitioners are perhaps struggling to verify capabilities of equipment for solving problems as a result. This leads to increased risk for clients and a commensurate reduction in the perceived value of geophysical solutions such as towed TEM.

TEM Configurator

To counter this trend, a new software tool is being introduced, in this paper, to make it easy for practitioners to make sets of layered-model type curves for virtually any transient electromagnetic configuration. The software, '*TEM Configurator*' is being provided as a freeware product by the principal author. Delphi Object Pascal source code is being provided for the configuration file reading and writing routines and the full program executable is provided (find links from www.GroundwaterImaging.com) .

Graphical verification of configuration parameters

TEM Configurator provides an interactive graphical interface for preparing and reading transient electromagnetic equipment configuration files. It works, interchangeably, with Aarhus Workbench GEX files and with new, similar, but extended, format TDC time domain Configuration files. This new format opens extended configuration description capabilities and is simpler for machine reading. Parameters are displayed in interactive menus with some explanatory graphics. Figure 3 presents an example of explanatory graphics designed to help verify if loop coordinates are entered correctly.

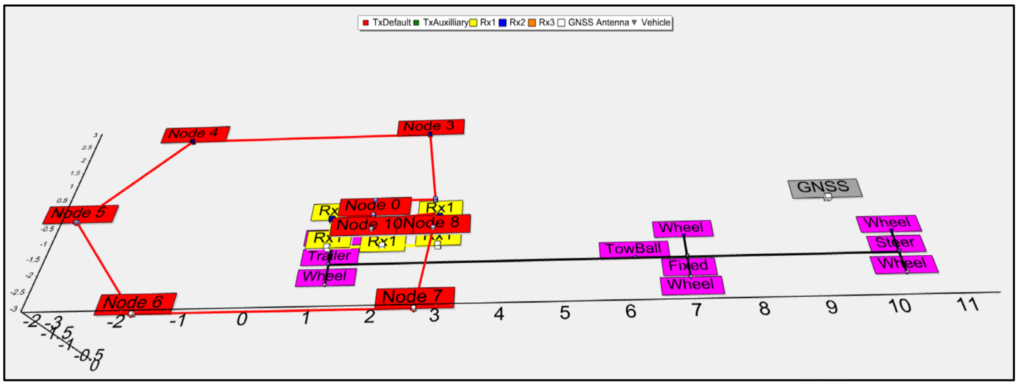


Figure 3. TEMConfigurator displaying loop coordinates from the Wallaby overlapping receiver loop configuration file.

Type curve generation

As a wrapper for the forward modelling and inversion code - '*AarhusInv64.exe*' (Auken, Christiansen, et. al., 2015), TEM Configurator provides abilities to both make and display sets of type curves for any layered-model and/or supported TEM configuration variation. Figure 4 gives an example where a Slingram 'front' loop added to a Wallaby configuration has been rotated from Z to X orientation over half-spaces ranging in resistivity.

Interactive comparison of field data with type curves

TEM Configurator facilitates overlaying of actual data, time constant curves, and noise threshold curves on forward model curves, which can be quickly and interactively adjusted so that students and practitioners can try varying parameters manually to see and learn the influence each has on the type curves. This is invaluable for evaluating system response and for verifying that systems are functioning and understood correctly. An example of Wallaby high moment system response determination is presented in figure 9.

Detectability of contrast between layered models

TEM Configurator provides detectability criteria contrasting models for any selected configuration. A curve of detectability of the contrast between the models is plotted as signal to noise ratio with respect to time. A sum of detectability for the gates is provided, representing the ability to detect the contrast using the entire curves, such as is relevant for an inversion routine. Using this facility, practitioners can predict, prior to heading out to attempt surveys, if the equipment and configuration they propose to use is likely to succeed in resolving expected contrast within a given precision. By plotting a whole set of type curves plus the detectability curve contrasting the first two of the type curves, users can verify how deep in the earth they are likely to be able to chase a particular feature, for example conductive basement. Figure 5 presents an example of a detectability curve.

Equivalence, in which different layered earths produce very similar forward models, results in ambiguity regarding interpretation of modelled data even should detectability of a contrast be high.

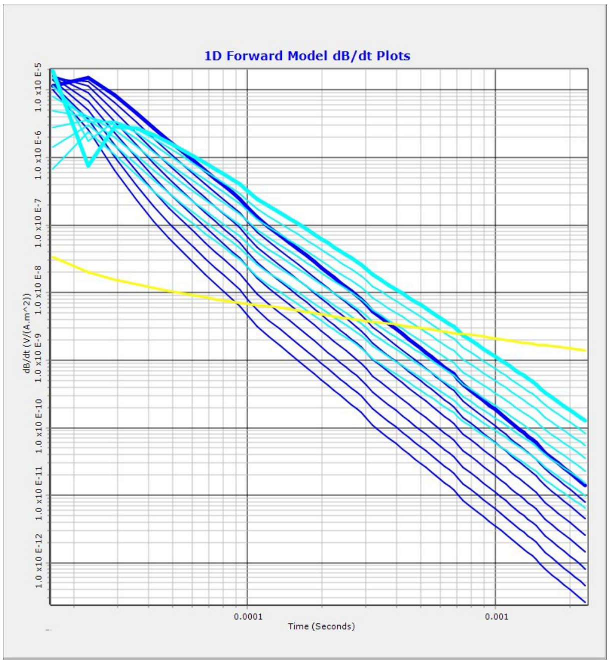
Blue - Receiver Axes with X-Orientation.

Aqua - Receiver Axes with Z-Orientation.

Yellow - Noise @ 1mV=2e-9 V/(A.m^2) with 0.5slope.

In early channels, X-Orientation signal dominates making Z-Orientation data sensitive to tilting.

Note that X-Orientation could also have a dominance of metal vehicle response as it couples axially with the vehicle.

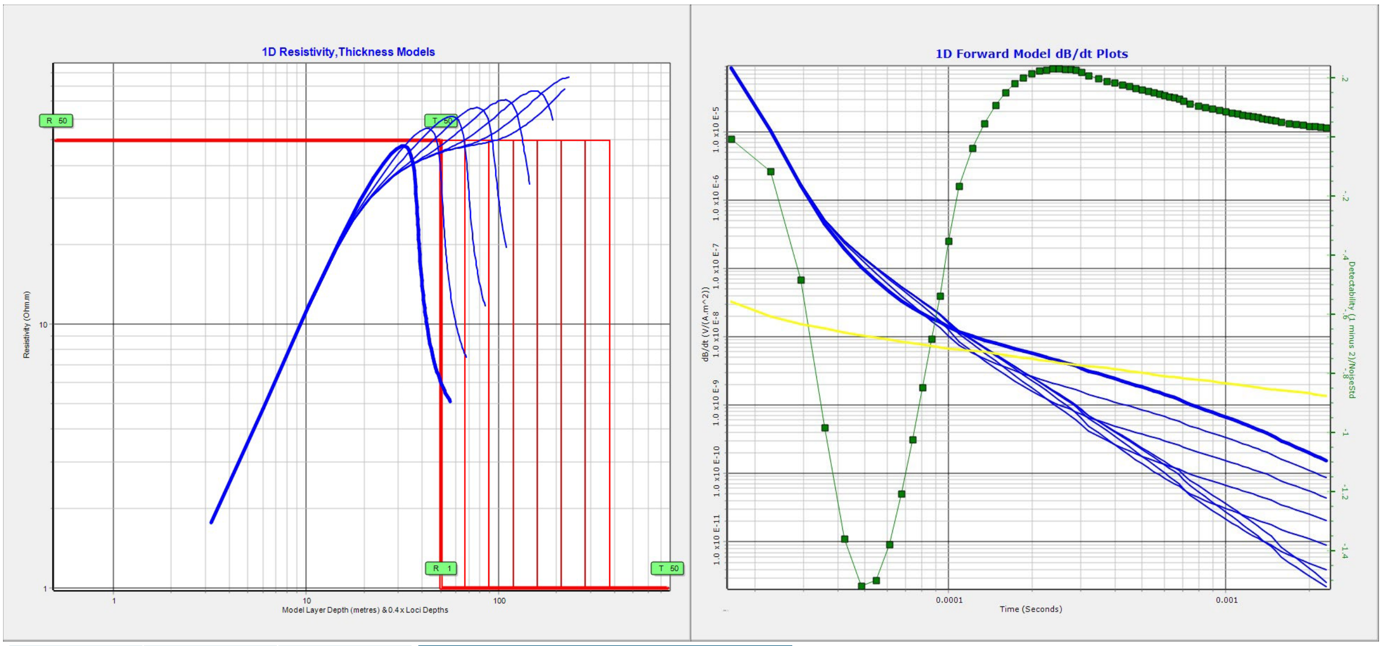


Halfspace Model Resistivities:
Starting with the bold line are:
1 – 5.0 ohm.m
2 – 6.7 ohm.m
3 – 8.9 ohm.m
4 – 11.9 ohm.m
5 – 15.8 ohm.m
6 – 21.1 ohm.m
7 – 28.1 ohm.m
8 – 37.5 ohm.m

This analysis is also relevant to other instruments. tTEM, which has ONLY a Slingram Z-component loop, is vulnerable to Z and X orientation mixing as the short-base sled pitches across rough ground.
Loupe collects only Slingram data but in three components and they model data as change in total field, thus eliminating the orientation sensitivity problem. An additional problem, however, is generated when a relatively low sensitivity coil is used to detect X-orientation data and the high noise on this component is mixed into total field data, unduly affecting the noise floor.

Observing this data we can see that a 20 degree pitch change will change the 2.8e-5 z-component data at 30uS over a 5 ohm.m half space to (2.8e-5).(cos(20)+(8.0e-5).sin(20)=5.36e-5 or 1.91 time of the correct value. On tussocky or ploughed ground a 20 degree tilt on a short base sled is common.

Figure 4. An example of type curves generated with TEMConfigurator. Wallaby front loop orientation comparison and signal stability.



Layer	Resistivity	Thickness
1-Alluvium	50 Ohm.m	10.0m 13.4m 17.8m 23.8m 31.6m 42.2m 56.2m 75.0m
2-Basement	1 Ohm.m	infinite

Noise: 2e-9 @ 1mS with slope of 0.5

Figure 5. Evaluation of a detectability curve (Green) for a given noise threshold (Yellow) for forward models (Blue) of layered models (Red) as given in the table included for Wallaby In-loop configuration with 36 Amps and one Tx loop turn. The left graph presents forward models as late time apparent resistivity versus 0.4 x Loci Depth while the right graph presents the same forward models as dB/dt versus time. Detectability is calculated contrasting the heavy blue curve with the adjacent curve. The noise threshold in this example is high such as is typical for short stack times and rapid travel over rough ground.

DIRECT CURRENT AND TRANSIENT EM MODELLED TRANSECT COMPARISON

Near Dubbo, NSW, Australia we collected and modelled both direct current and transient electromagnetic datasets along a transect over reasonably resistive geology. All the datasets have been plotted in the same way using the equal area colour distribution optimized for the Wallaby resistivity dataset. The histogram and colour scale are presented in figure 6.

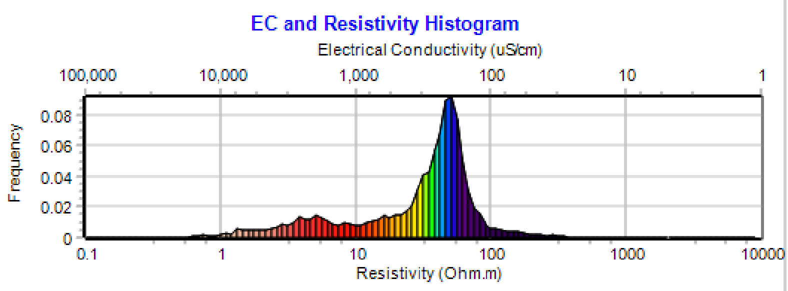


Figure 6. Wallaby transient electromagnetics resistivity distribution at the test site – used to colour the remaining figures.

Direct current ERT

A Lippmann Earth Resistivity meter and Active Electrode System (https://www.schwartech.de/#/geoelektrik_de) was set up in a transect 700m long across the site using the Lippmann ActEle leap-frog cable system with six 100m long cables such that electrode combinations across 600m of transect could be conjunctively used at any one time. Both Zhou (Zhou, et. al., 2020) and Wenner configurations were applied using GeoTest software. (https://www.geophysik-dr-rauen.de/E_Index/E_geot_geotest/e_geot_geotest_features/e_geot_geotest_features.htm). Results of Wenner and Zhou configurations, modelled with Res2DInv, are similar. The Zhou results, are presented in figure 7.

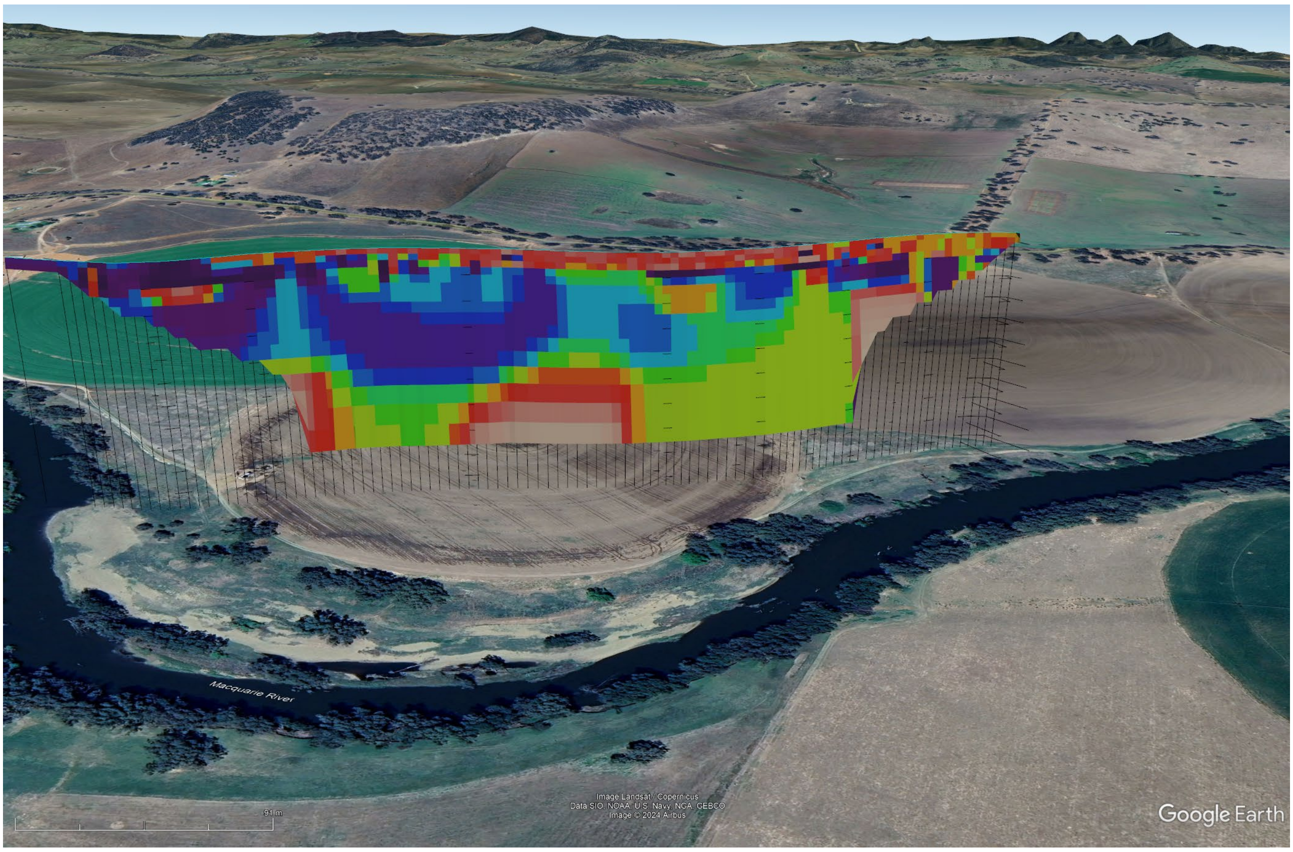


Figure 7. Direct Current Electrical Resistivity Tomography – Zhou array configuration. Modelled resistivity is projected up 160m using the colour distribution of figure 6.

System response modelling - Wallaby

A segment of Wallaby data from near the river end of the transect was averaged and a discrete layered model for the Zhou, Wenner and 50x50m loop datasets was created. This model was then forward modelled and displayed, with the field data, in TEMConfigurator as shown in Figure 9. Numerous configuration parameters were temporarily adjusted, and forward modelling repeated to verify to which parameters the model is sensitive so that sensitive parameters could be further investigated. Finally, system response was determined from this field data minus forward model comparison and the system response was then subtracted from entire datasets of the same configuration. Table 1 presents the discrete layered models estimated, and the forward model selected for subtracting from Wallaby data. See that model from 50x50m loop TEM data, uncorrected for system response, has been largely ignored.

Zhou			Wenner			TEM 50 x 50			Fwd Model		
From	To	Res	From	To	Res	From	To	Res	From	To	Res
0	16	180	0	10	200	0	30	1000	0	16	180
16	30	40	10	20	50	30	60	15	16	30	40
30	72	120	20	60	120	60	70	5	30	62	120
72	inf	20	60	inf	45	70	inf	30	62	inf	20

Table 1. Determining a layered model at the test site to forward model.

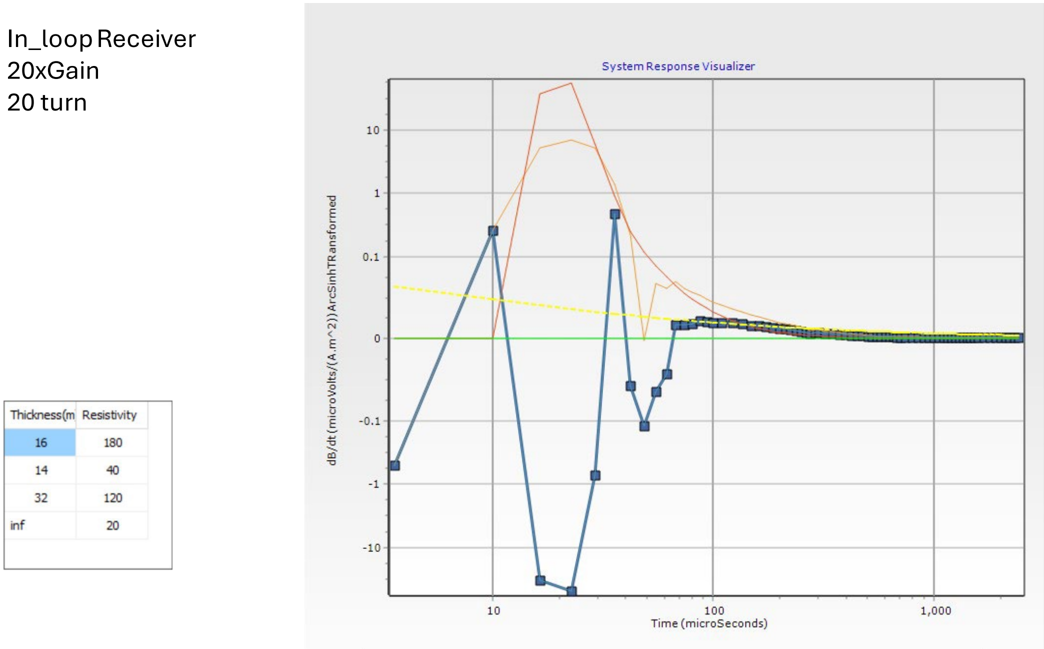


Figure 9. High moment (38 Amps x 32m^2) Wallaby system response assessment for the in-loop receiver with 20 turns and 20x pre-amplification. Field data is displayed in orange, assessed noise threshold in yellow, and the forward model in red. Finally, the blue system response curve was obtained by subtracting the model curve from the field data. The log scale results in the bulk of the graph being dominated by part of the data that is never used in modelling of high moment data. Earlier time data is affected by digital delays in the electronics, self-response decay and under-damp overshoot. Later time data is affected by metallic induction with the towing vehicle and this is the primary response that must be removed as part of the system response. Realise that this exercise is applied at a resistive site, deliberately, and that much of the system response correction becomes much less significant at more conductive sites, and that there are electronics delays prior to the ramp.

Wallaby and Wallaroo

Data was collected next using the Wallaby and Wallaroo systems along approximately the same transect. Modelled In-loop Wallaby data is presented in figure 10 with system response corrected prior to modelling. Meaningful modelled data has been generated with depth of investigation characteristic of approximately 160m. Modelling without system response removal, in contrast, generated meaningful data only to a third of this depth with artefacts at all depths so for such a resistive site, the correction is very important.

CONCLUSIONS

TEMConfigurator, as an interface to AarhusInv, has made possible rapid, interactive generation of sets of graphed forward models and comparison of them with field data. Effects of any configuration change on the forward models can be readily visualized. Sets of anticipated layered resistivities and depths can be forward modelled prior to committing to survey with a particular TEM configuration and detectability of anticipated features can be predicted. Appropriate towed or airborne TEM systems can then be selected for use in survey.

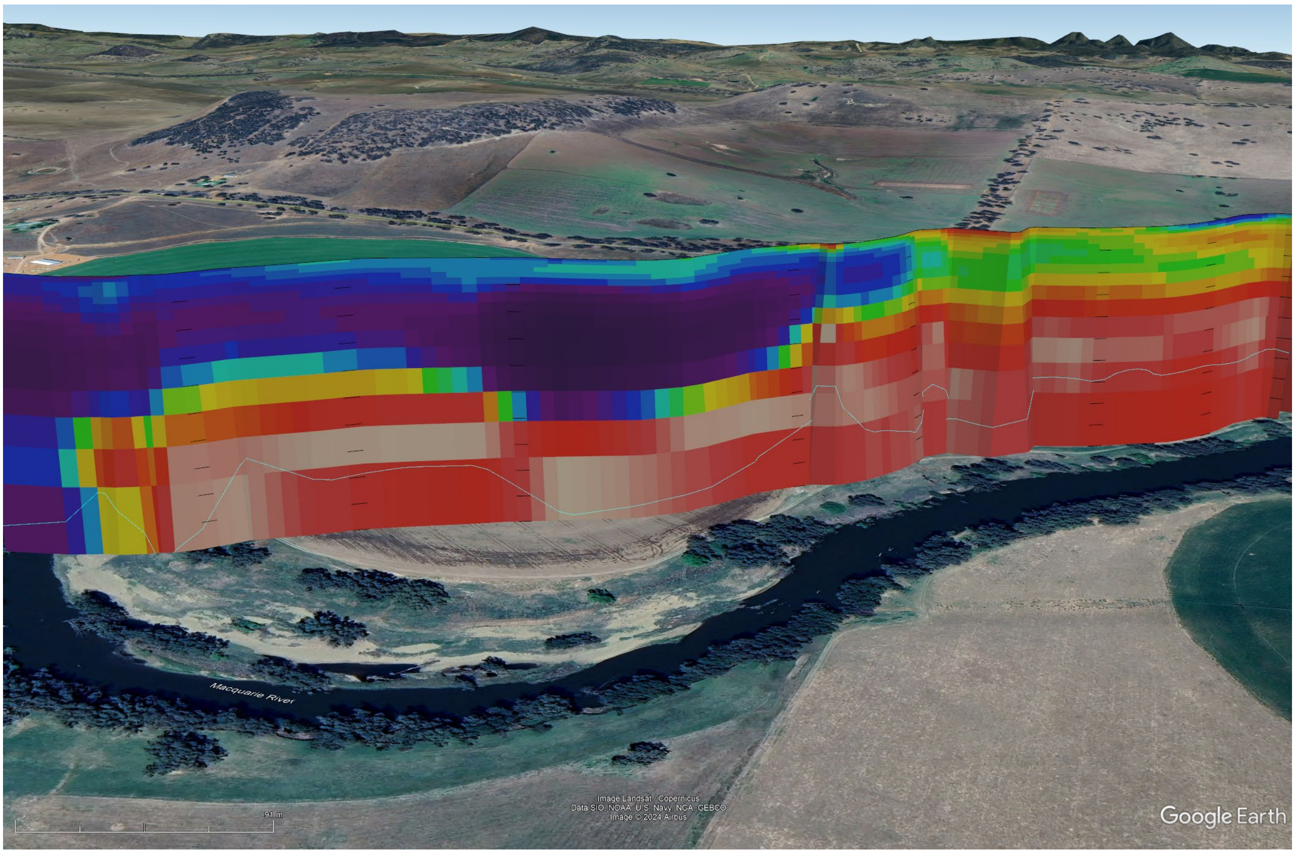


Figure 10. Wallaby In-Loop transient electromagnetics. Modelled Resistivity projected up 160m (525 feet), 2 Parallel 1 Series Turns, 38Amps, 150 Watts.

Wallaby and Wallaroo TEM antennae platforms have been evaluated and found to be suitable for imaging bulk earth electrical conductivity from 0m down to 160m deep in moderately resistive geology with conductive basement if system response is accurately removed. Detectability of features is, however, strongly dependent on the whole geological model. Overlapping receiver and transmitter loops of the Wallaby platform are more effective than Slingram loops when commercial productivity rates over rough ground must be achieved. Wallaroo, with a Slingram receiver loop, and carried by three persons, or propelled by an electric tractor, is more effective on small jobs when the cost of towing Wallaby on a dedicated float trailer is prohibitive, or on rough terrain jobs, where a large towing vehicle could get damaged or stuck.

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