Alberta Provincial Groundwater Inventory Program,

Calgary-Lethbridge Corridor

Geophysical Survey:

Ground Time Domain Survey Data and Report on AeroTEM Airborne Data and Inversion

For

ERCB – Alberta Geological Survey

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prepared by

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1. SURVEY OBJECTIVES

Initially, the objective was to validate the inversions of the AeroQuest airborne time domain (AEM) data collected in spring of 2011 by the AeroTEM III and secondly to verify the accuracy of the AEM data. However, as modeling of the ground data proceeded, a third objective arose. This objective was to determine to what extent time domain (TEM) data could resolve the resistivity structure of the ground.

It should be noted that time domain (TEM) data excites the ground through a physical process termed induction often expressed through Faraday's law. This excitation process can is very different from excitation through a current driven into the ground such as in resistivity surveys. Thus, generally, we are determining inductive resistivities rather than galvanic resistivities. However, in such geologies as covered by this AEM survey, these two resistivities should be very comparable.

As part of the overall objectives, the ground TEM surveys were designed to examine how laterally uniform are the ground resistivities. This is important for two reasons. First, the AEM survey lines are approximately 700m apart and thus imaging the ground with such line spacing would only be appropriate if the ground resistivity was generally uniform over this scale. Secondly, the AEM inversions were performed by inverting a short window of stations along the line to obtain a one-dimensional (1D) model. Such an approach is only valid if the ground resistivities vary slowly over the survey area.

2. SURVEY EQUIPMENT AND OPERATORS

Generally speaking, TEM equipment using a roughly 50% duty cycle with a coil sensor are utilized to image the resistivity structures for such applications. The supply of such equipment is somewhat limited and Geonics equipment is quite often used for this reason. Recently, the use of magnetometers have been tried for such applications but as they measure the magnetic field and not its time derivative, they show less discrimination in the layering although theoretically they cold resolve deeper. T

he Geonics receiver unit is called the ProTEM receiver and it can be used with various transmitters. As the primary transmitter, the EM57 was chosen as it is gas generator powered and thus offers more current input than the EM47 which is battery powered. Various coil sensors are offered for use with this equipment by Geonics but the air filled coil of 100 square meters effective area provides a better bandwidth than their 3D coil and it has been used extensively over the last three decades and is known to be quite accurate. The smaller air coil of 31 square meters was also utilized briefly with the EM47 transmitter.

Frontier Geosciences of Vancouver was chosen as the operator. They are long time operators of such equipment and their price was the lowest offered. Generally, production levels were low primarily due to problems synchronizing the transmitter and receiver. This is not unusual with this particular equipment due to automatic synchronization software and the lack of drift monitors. Thus, data was collected in both reference mode (cable) connection and crystal clock synchronization mode. In crystal mode it is possible to measure further from the loop as the cable is of limited length. The reference data provided assurance that the crystal synchronization was correct. In some cases, the crystal synchronization data had to be discarded.

It should be noted, particularly for geophysicists reading this report, that often Geonics data is delivered not properly synchronized. The operators are unaware that there are problems with the automatic synchronization and generally geophysicists to do insist on monitoring procedures for drift in this instrument.

3. SURVEY DESIGN AND SURVEY SITES

The ground TEM surveys were initially designed to use 400m by 400m loops with NS and EW lines through the centre of the loop with line lengths approximately 1km. This design was chosen for two reasons. First, such a design is capable of determining just how laterally uniform the resistivity structure is over the scale of the AEM line spacing and secondly such a survey should be able to resolve the resistivity down to a depth of several hundred metres.

Each site was designed for the data to be collected in one day allowing for 5 sites to be collected within the project budget. However, the first day's results indicated that the original objectives for each day could not be accomplished. The operators were not able to collect all the data requested for each day. This was primarily caused by two issues. First, the travel times from motel to site were lengthy and the amount of daylight hours limited. Secondly, there were problems synchronizing the system in crystal model which required more data to be collected in reference mode. This is a lengthy procedure due to maneuvering the reference cable and also required the need to repeat stations in both modes.

As a result of these problems, production in terms of numbers of stations collected was low. Because of this, it was decided to reduce the loop size to 200m x 200m to reduce the time to layout and recover the loop thus allowing more time to collect data.

3.1 Site Locations

The locations of the five test sites are shown in **Figure1** displayed against the regional geology.

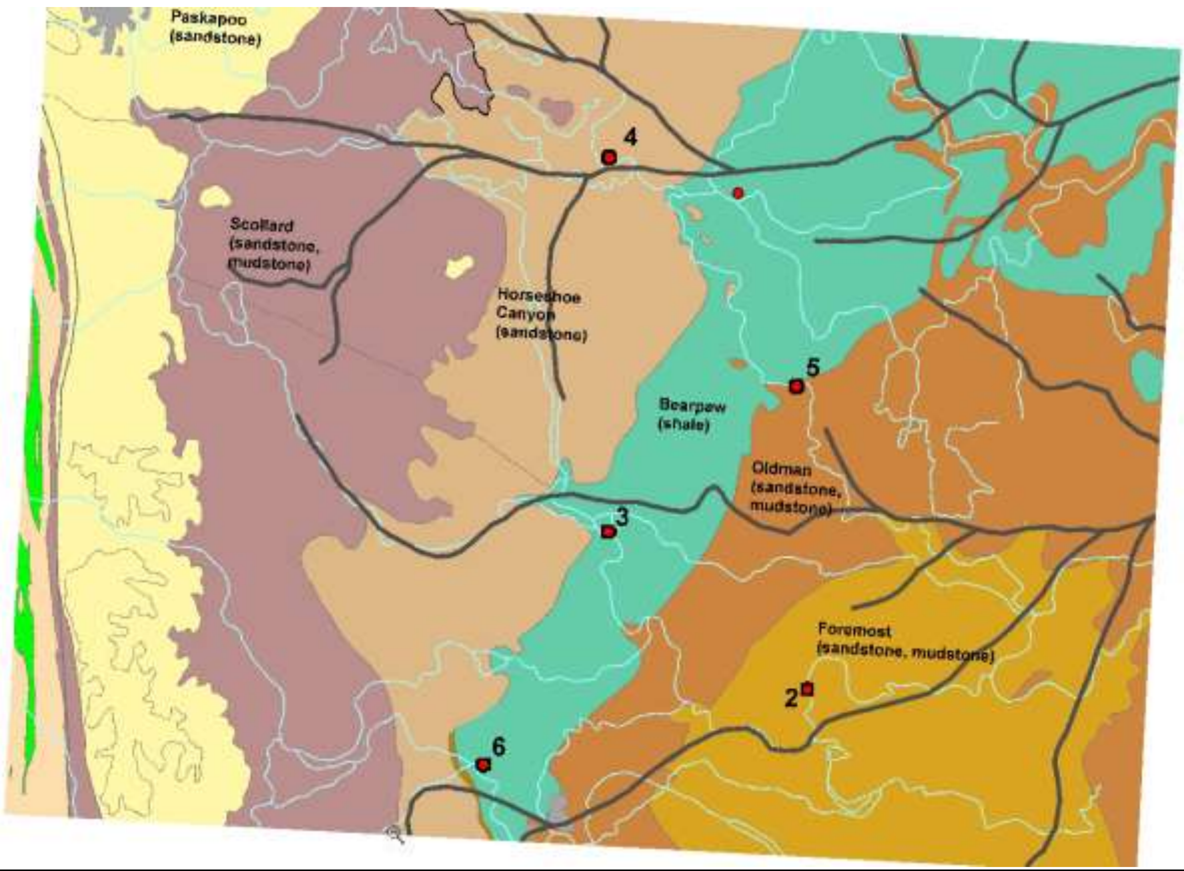


Figure 1: Site Locations – 1-5 (red squares) against regional geology.

The proposed survey details of each site are shown with satellite maps in Appendix I.

4. QUALITY CONTROL PROCEDURES

First, it should be understood that not all data is collected correctly and secondly, all instruments have their limitations and weaknesses apart from operator errors. As such, the data collected at each station must be examined from the perspective of not only data repeats but also the data at neighbouring stations as well as the general nature of the data response.

At each station measurements were to be repeated and averaged for a period of 2 minutes. This means that for 30Hz data, 3600 measurements were made at each station and then the data averaged over those measurements. The object of this is to reduce instrument and environmental noise in the measurements. The instrument in question, ProTEM from Geonics Ltd, unfortunately does not record the length of measurements correctly as the data processing and data output files from the instrument have several problems which apparently cannot be corrected by the company. Thus, we have only the statements of the operator that such extensive measurements were made. However, repeat 2 minute measurements were made a virtually all stations. Thus we could examine the repeats to see where noise may exist in the measurements. The data repeats were generally excellent but any noisy measurements were removed prior to modeling and inversion.

The physical scattering process of low frequency time-domain processes is a diffusive process in this type of conductive environment. Thus, the responses are approximately predictable from station to station. Thus, obvious instrument failures or effects of very local, small conducting objects could be observed and this data removed.

As the range of resistivities is known for this environment, forward simulation of the data allows a further quality control procedure and one that was used extensively in our procedures.

EMIGMA (Petros Eikon) software was used for the modeling. This software represents the instrument's system response accurately and has been tested and used extensively for almost 2 decades verifying its accuracy.

5. INVERSION METHODOLOGY

The first stage in our inversion process is to define an approximate model based on what is known of the resistivity structure in the region. This is then compared to the data allowing quality control and also giving insight into the resistivities imaged by the data. A few adjusted models are then made to understand the range of resistivities possible.

The second stage in the inversion process is to define a starting model consisting of a reasonable number of layers. In this situation, it was quickly found that generally 4 discrete layers plus a basement was a suitable starting models. Initial resistivities and reasonable thicknesses were then defined by forward modeling to obtain an approximate model which was geologically viable. The inversion process then consists of attempting to fit the under-parameterized model through a series of inversion steps. The technique is essentially a linear technique (Jia et al, 2011, David and Groom, 2010) in which the model and its model derivatives are determined through forward modeling (EMIGMA) and iterative steps are made to reduce the difference between data and model (residual) within prescribed limits for resistivities and thicknesses. As the data was generally very clean both in time and spatially, a weighted residual was normally sought below 1%.

An inversion model is then obtained at each station for each site for the specific system configuration used in the collection of that data. These inversion models are constrained not only in terms of both resistivity and strata thicknesses to be geologically but also for models which vary smoothly from site to site. After this first process, several inversion models are chosen at various stations and these models tested as a single model for the entire site.

As the inside loop stations are very sensitive to the shallow resistivities and the outside loop stations more sensitive to the deep resistivities, a model was sought to fit both inside and outside. Generally, this was obtained. However, in some cases, it was determined that although the inversion process was still scientifically acceptable, there were small spatial variations in resistivity. These variations were determined and sometimes 2 slightly varying models were determined.

At no site was it determined that the three-dimensional effects were strong enough to require three dimensional modeling of the data.

6. RESULTS OF ANALYSES

During our analyses, many models and inversions were performed. Upon each of these, synthetic data is produced which was used to compare to the data to determine how each model or inversion fit the data for all time channels. Displaying all or many of these data fits would make this report overly long and such displays would not be of relevance to many readers. Therefore, we will place some examples in Appendix II to allow some idea of how we chose accurate models over less accurate models.

The entire set of models and inversions will be provided in an EMIGMA database. For examination, a license is not required to view the results as a free version allowing one to view and display results is provided on our website, www.petroseikon.com.

6.1 Site 5 – Dec 2, 2011

A 200m by 200m loop was used with a 30 Hz basefrequency with a sensor coil having an effective area of 100 square metres. Data was collected in both Reference (REF) mode and Crystal (XTAL) synchronization mode. In most cases, measurements with taken with 2 minute stacks and each station was repeated twice to check noise levels. In all cases, data was well repeatable for all 20 time channels as would be expected for such long stacks in such conductive environment. The current was generally 7 Amps for all the data at this site. The currents for all sites ranged between 7 and 9 Amps.

Reference (REF) Mode Data

On an EW Line, data at 3 stations were collected at 200W, 0W, 200E relative to (0,0) being the relative centre of the loop. On a NS Line, data were collected also at 3 stations: 200N, 0N, and 200S. The centre point data repeated well for 0W and 0N.

In the application of fitting the data to a one dimensional (1D) model where resistivity is only a function of depth, we are seeking a model which is approximately the same for all data points obtained from a single loop. In this particular case, the data at the 4 data points which are 200m outside the loop should be very closely the same. This is because for a 1D environment , the response at these 4 stations would be precisely the same if the loop was perfectly square and the positioning exact. The loop's geometry is checked via measurement of about 20 locations on the loop's wire through GPS measurements. In this case, the loop is as square as can be determined via the GPS instrument that was used. For this site, variations from a square were small.

200S, 200N were not as similar as one would expect but 200W, 200E were quite similar. 200S was also quite similar to 200W, 200E. Therefore, 200N was deleted and an average taken of the other 3 stations – 200E, 200W, and 200S. This averaging minimizes errors in the data as well as geological variations from a 1D ground.

Inversions were then performed on the resulting two points, centre and 200m outside the loop. The centre model was more conductive at surface than the model for the outside station with a cover of about 1 Seimen (S) as opposed to 11/17 S for the outside location.

The general model is 10 ohm-metre (Ωm) for 12-16m, more conducting at 5-7 Ωm to 100m and then slightly more resistive at 8-9 Ωm to about 200m depth. Resistivities below 10 Ωm would imply more clay like materials or rocks than in the quaternary cover.

The best centre point model is called ***centre_ref 2_nobase*** and consists of

10 Ωm for 11m, 6.7 Ωm for 30m, 8 Ωm for 52m and then 9.5 Ωm.

For the airborne data (AEM), the resistivity model must be more resistive at depth. This is discussed again below.

Crystal (XTAL) Mode

In this mode, data was collected at 9 stations on the NS line at 200N, 0N, 200S, 250S, 300S, 350S, 400S, 450S, and 500S. The data at 200N was clearly not correct likely due to synchronization issues. Additionally, data was collected at 3 stations on the EW line at 200W, 0W and 200E.

NS Line

At 0S, 200S the REF model above (***centre ref 2 no base***) fits the data well as expected confirming the data is well synchronized. For the remaining southerly stations, this model fits the data reasonably well although at these stations the data indicates that the area south of the loop is slightly more resistive both on surface and at depth than in the centre model above.

At this stage, a joint model inversion was performed using all good stations on the NS line.

Best Joint Inversion Model: *MultiLoc2_MarqInv_5*

11 Ωm for 18, 5 Ωm for 17m, 8 Ωm for 71m , 8.5 Ωm for 84m, then 5.3 Ωm

While this is not the best model for any station, it is the model that best fits all stations. A surface resistivity of between 10-12 Ωm is certain with a conductive zone below of between 5-6.5 Ωm followed by slightly more resistive strata. There is evidence of a further conductive strata below that and then higher resistivity below.

EW line – 200E, 200W and 0W

Both the REF mode -***centre ref 2 no base-,*** the specific model for 500S and ***MultiLoc2_MarqInv_5*** described above fit the centre station and 200W quite well. But the early time decay at 200E indicates a slightly more resistive cover to the east.

AEM Model Site 5

The AEM Model for the airborne survey line through the loop indicates the same resistivity at surface as for the ground data but no significant conductive strata is observed in this data. The conducting strata at between 10 and 18 metres is clear in the ground data.

Model: Site 5 AEM

10 Ωm for 20, 8.8 Ωm for 18, then 13 Ωm

For comparison, the ground model

11 Ωm for 18, 5 Ωm for 17m, 8 Ωm for 71m , 8.5 Ωm for 84m, then 5.3 Ωm

If we apply the surface data models to simulate the AEM response, the results produce too large a response at later times. However, if we assume the altitude of the AEM data is incorrect and increase the altitude by 10m and omit Ch1 from the AEM data then a slightly varied model from the ground model fits the data reasonably well. The only other explanation is that the airborne system is not working properly except at the early channels.

Site Conclusions: The main conclusions from this site are

a) The cover is more resistive than the strata below
b) There is a mild conductor below the top layer
c) Moderately low resistivities persist to some depth likely more than 200m
d) The AEM data as it stands does not agree with the ground data
e) Precise determination of the resistivity structure to depths below 200m will require a survey as originally planned

6.2 Site 4 Dec 3, 2011 200x200m loop, 100 sq.m. coil and 30Hz base frequency

REF Mode data

5 stations were collected on an EW line from 400W to 200E at 100m increments skipping the loop wire at 100W and 100E. A NS line was also collected with stations at 200S, 200N and at the loop centre.

EW line – 5 stations

The inversion process resulted in these models:

***MI5 0N 400W* model: 20 Ωm for 53m, 5.7 Ωm for 22 and then 6.6 Ωm**

This model fits 400W, 300W, 200W. However, the centre needs lower resistivities at depth.

Centre Model: *MI5 ONOE* – 23 Ωm for 38m, 7.7 Ωm for 27m and then 5.9 Ωm

Note 1: 200E data requires more resistivity at surface than 200W. This could be data issues or could be the lack of spatial uniformity in the resistivity.

Note 2: Generally, it is not physically reasonable to suggest that data at the centre of the loop has better resolution of resistivity at depth. This is because deeper structures are generally imaged by later time data and by later time, the centre of the current distribution is generally well outside the loop. That the centre requires a slightly higher resistivity at depth is more likely an instrument failure. Late time data errors inside the loop for Geonics data is quite common.

NS line – 3 stations

The model above, *MI5 0N 400W* , fits data at 200N, 0N but 200S does not fit the model. 200S requires thicker cover (60m) similar to 200E.

XTAL Mode data

Data at 7 stations were collected on an EW line with each station repeated twice from 500W to 300E at 100m steps omitting the loop edges. The original logistics report is incorrect in stating that 200E and 200W were not read twice.

The resulting model is obtained first by attempting to find a single model to fit all the data and then by a joint inversion of the data at all the stations for the best fitting single model.

Overall Model: *Unif MultLoc3*

23 Ohm_m for 46m, 7 ohm_m to a depth of 86 and then 6.5 ohm_m.

However, this model does not fit centre point so well. The model *MI5 0N0E* used for the REF data at the centre point does fit the XTAL centre point. Namely,

23 Ωm for 38m, 7.7 Ωm for 27m and then 5.9 Ωm

First, these results indicate that the XTAL data is synchronized correctly. Increasing the thickness of the top layer to the west of the loop, produces models which fit the western data better than the center point model. At 500W, this depth reaches the maximum but likely 400W is a better choice to pick the depth. The depth of the top layer at 400W is 44m.

AEM Model and Data:

Line 10400 of the AEM data passes through the SW corner of the loop. A simple 2 layer model is all that is required to fit the data. The following model represents the data in the vicinity of the loop.

2 layer: 52 Ωm for 52m with 13 Ωm below.

This model disagrees significantly from the ground model particularly with regard to the resistivity of the cover strata but also the resistivity of the next strata below that. The AEM data was modeled with MI5 0N0E to see how it would fit a reasonable ground model for the site..

However, as indicated by the AEM inversion model, the amplitude of AEM data at early time to mid-times is too low to agree with the ground model. However, the decays of the measured data and the simulated data are very similar utilizing this model.

Appling a multiplier to all data of 1.64 produces modified data that fits the ground model reasonably well. This result seems to confirm one issue that was implied in our report on the AEM data in 2011. That issue was that the equipment provider was experiencing problems with controlling the output of the transmitter to a sufficiently fine accuracy to provide data suitable for optimal inversions.

Site Conclusions: The main conclusions from this site are

a) Again, the area appears to consist of a more resistive cover. In this case, thicker than for the previous site
b) The strata below that is more conductive and in this case, it is less conductive than the previous sie.
c) The more conductive strata persists to some depth and resolution of the thickness of these conducting strata cannot be resolved without a somewhat more comprehensive ground survey
d) The AEM data does not agree with the ground data. There appears to be an amplitude factor in the AEM data whereas the decays of the AEM and ground data agree.

6.3 Site 2 – Dec 1&4, 2011

Data was collected at Site 2 on 2 days.

Dec 1 - 200x200m loop, 100 square metre coil, 30Hz base frequency

Five stations were read all in the reference mode. These consisted of the station at the centre of the loop and 4 stations each 200m from the centre in four directions – E,W,S,N. Each station was read twice and the centre station was repeated a further two times.

200N was removed as anomalous to the other stations. That is, if we are to interpret through a one dimensional model, the data at 200E,200W,200S,200N should be the same except for geological, instrument and environmental noise.

After removing 200N, we averaged the data from the three remaining stations at 200m outside points. Prior to averaging the variations in the data between these three stations was small.

A model was then derived which fit the centre station and the average results from the 3 stations that were outside the loop and 200m from the centre.

***Dec 1 S2 Model*: 17 Ωm – 35m, 6.6 Ωm – 45m, 7.7 Ωm – 30m, 6.4 Ωm**

All these layers are required for precise fitting of both inside and outside the loop and no additional layers are required. The model consists of a moderately resistive cover follow by a series of conductive layers. Resolution depth is in total approximately 110m. That the resistivity of layer 2 is lower than layer 3 is resolvable and if the data is accurate, the bottom resistivity is lower than layer 3. However, it cannot be said for certain that layer 2 and layer 4 have different resistivities.

AEM Model for Site 2: Using *Dec1 S2* as a starting model, we derive the following models for the AEM data near the Site 2 loop.

Dec1 S2 model is not a bad fit on the east line (L20310) except for Ch1. However, the decay is a little too slow at late times. These are the derived models for two lines; just east and another just west of the loop over a length of about 600m NS about the centre of the loop.

L20310 – east of site – **17.4 Ωm – 38m, 8.0 Ωm – 15m, 10 Ωm – 34m, 15 Ωm**
L20320 – west of site – **16.4 Ωm – 50m, 8.0 Ωm – 15m, 10 Ωm – 60m, 4 Ωm**
as compared to *Dec1 S2:* 17.0 Ωm – 35m, 6.6 Ωm – 45m, 7.7 Ωm – 30m, 6.4 Ωm

These two AEM models are reasonably consistent models implying relatively uniform ground structure in the area as suggested by the ground data. This points to no amplitude issues in the data between the two flights. However, the AEM model has significantly more resistive strata beneath the cover layer when compared to the ground model. When the ground model is used to simulate the airborne survey, the simulated data has a slower decay in late channels than the actual data. There is no obvious geological reason why the two surveys would disagree in the substrata resistivities.

This might point to an inconsistency in the coil decays within one or both of the systems. That is, each coil including those with the same design may have a different intrinsic decay from any other coil. The system and the coil should be designed such that the intrinsic decay of the coil is not seen in the data. This, however, is not always the case in our experience.

Dec 4 200x200m loop, 30Hz basefrequency, 100 sq.m. coil

Data was collected at Site 2 also on December 4, primarily to acquire XTAL data further outside the loop.

REF data

Data was collected at 4 stations on a NS line: 0N,200N,300N,400N. The December 1 REF model – *Dec1S2* - fits data at stations 0N,300N but no so well at 200N and 400N.

A model was thus produced to fit the 400N station:

***Model*: *MI4 400N* – 16.3 Ωm – 45m, 6.9 Ωm – 117m, 7.0 Ωm – 97m, 20Ωm**

as compared to

Dec 1 S2 Model: 17.0 Ωm – 35m, 6.6 Ωm – 45m, 7.7 Ωm – 30m, 6.4Ωm

One of the principal differences in the models is that the Dec1S2 model does not observe the bottom resistor. However, the MI4_400N model does not fit the data at 0N. This would possibly imply a more resistive basement to the north of the loop.

The AEM data to the north of the loop is in agreement that there is a more resistive basement to the north of the loop but the thickness of the conducting zone is much thinner in the AEM model just north of the loop than for ground model *400N.*

XTAL data:

Data was collected at 9 stations on a NS line from 500S to 500N at 100m intervals missing loop edges at 100N and 100S.

The reference data model – *Dec 1 S2* – fits the XTAL data well except at the extreme southern and northern points. A combined inversion of all the data produces the model – *MultiStat 5layer 3*. This model likely produces more resolution at depth that the REF model due to the use of data from stations further outside the loop. The conductor at extreme depth is questionable in our experience.

***MultiStat_5layer_3*: 16.3 Ωm – 33m, 6.7 Ωm – 129m, 4.7 Ωm – 78m, 33Ωm – 53m, 15 Ωm**

Dec 1 S2 Model: 17.0 Ωm – 35m, 6.6 Ωm – 45m, 7.7 Ωm – 30m, 6.4 Ωm

The conductor at the base is not definitely there and this model fits the data to the north of the loop somewhat better than to the south. Note, however, in this case the ground data does begin to observe an increase in resistivity at depth and the estimate of that depth is approximately 240m. Site 5 also showed indications of increased resistivity at these depths.

AEM fit to ***MultiStat_5layer_3***:

For Line 30310 to the east of the loop, the model fit is good except that the model is too conductive at depth. For L30320, the model is far too conducting at depth. More explicitly, if the ground were as conductive at depth as the ground data indicates then the AEM data would be significantly different if the AEM data were accurate.

However, AEM data appears to sense the top layer as 2 layers, one slightly more conducting than 16 and the other more resistive. This is entirely possible as the airborne loop has a smaller area and thus may be able to differentiate within the cover layer when the ground systems cannot. The conductive layer below is appropriate with an increase in resistivity even deeper but the data requires a conductor at depth which we do not believe exists. The models vary slightly for the lines on either side of the loop.

	AEM East line	AEM West line	Ground
Top resistivity	15	10	16.3
Top thickness	27	11	33
2nd Layer Resistivity	24	30	16.3
2nd Layer Depth to bottom	40	61	33
3rd Layer Resistivity	6	4	6.7
3rd Layer Depth to bottom	67	75	162
4th Layer Resistivity	8	10	6.7

The discrepancy between the ground model and the AEM data is quite clear. When using the ground model to represent the AEM data, the measured and synthetic data diverge around channel 6 with the AEM response to ground model decaying slower that the data. This is caused not by the resistivity of the cover material but by the fact that the cover material continues to 33m depth in the ground model and then decreases whereas the AEM model has an increased in resistivity below the cover and then decreases in resistivity deeper than the ground model. The only physical possibility was that there was significantly more moisture content at depths 15-30m during December, 2011 than during the spring of 2011.

The main factor causing the difference between the AEM data and the response of the ground model to the airborne survey is in the more resistive material below the cover layer. That is the ground model and the airborne data agree on a resistivity in the order of 10-15 Ωm for the first 20-30m but thereafter the airborne data implies a resistivity of 24 Ωm or more to a depth of 40-60m whereas the ground data implies a resistivity of 16 Ωm of less than 6.7 Ωm below 33m.

Thus, one conclusion is that the AEM model compares sufficiently well with the ground model response but resolves to less depth? One should note that the AEM models do not fit the ground data as the model is too resistive at shallow depths but below the surface material.

Site Conclusions: The main conclusions from this site are

a) Again, the area appears to consist of a more resistive cover of moderate thickness 30m or more.
b) The strata below that is more conductive as at the other sites.
c) The more conductive strata persists to some depth of at least 160m. Resolution of the exact thickness of these conducting strata cannot be resolved without at more comprehensive ground survey
d) The AEM data does not agree with the ground data. There does not appear to be am amplitude problem but rather a decay problem indicating an intrinsic coil decay remaining in one of the data sets and that likely in the AEM data.

6.4 Site 3 – November 30, 2011

REF Mode Data

In REF mode, data was collected with a 400m EW x 300m NS loop using the standard 30Hz basefrequency and 100 sq.m. coil.

Data was first collected at two calibration points inside the loop then at the centre of the loop (0W) and at 100W, 300W, and 400W. The calibration points are inside the loop near a corner and close to the transmitter. These are devised as a means for checking crystal and reference synchronization at the start and end of each day. However, the survey crew could never manage to accomplish this objective properly or effectively and so this aspect of the survey was not continued after November 30.

Non-calibration points – 0W,100W,300W and 400W

It is our opinion that 400W cannot be fit with a 1D model for late times. We spent considerable time attempting to find a model and then time to convince ourselves that such a model could not be found. This is contrary to 300W, although only 100m east of station 400W. The response is entirely different between the two stations. Both 300W and 400W start negative as expected as they are outside the loop. 300W has a sign crossover in early mid-times at 1.28msec but 400W stays negative which is entirely unexpected. There is either a strong anomaly near 400W which must be relatively small or the survey location is significantly incorrect or the equipment has failed or was operated incorrectly.

A model was derived to fit the remaining data for stations 0W, 100W and 300W.

***MultLoc_MI5 model*: 145 Ωm – 11m, 3 Ωm – 3.3m, 6.5 Ωm – 60m, 7Ωm – 60m, 17.3 Ωm**

Resistor at the very bottom of the model is required for 300W but not for the inside stations. The data is only slightly sensitive to the exact resistivity of the top layer. The top layer must be a resistor but could be as low as 40 Ωm although something closer to 145 Ωm gives the best fit but this entirely depends on the precise accuracy of the data.

This model is similar to other sites except the top layer is somewhat more resistive and the conducting sequence somewhat thinner at about 145m. . This may be the reason that the resistor at depth is more resolvable than at other sites.

Calibration Points

2 points in the SW corner of the loop were read in REF mode. These points were both repeated twice and then twice again. The first set of measurements is obviously incorrect. The reason is unknown. The second set was very repeatable and produced a model somewhat different than the model above

MultiLoc2_MarqInv_5 model:

142 Ωm – 12m, 4.7 Ωm – 2.25m, 3.9Ωm – 34m, 14Ωm – 19m, 9.5 Ωm

as compared to *MultLoc_MI5 model*

145 Ωm – 11m, 3 Ωm – 3.3m, 6.5Ωm – 60m, 7Ωm – 60m, 17.3 Ωm

The model, *MultiLoc2_MarqInv_5,* is produced by a joint inversion of both calibration points. The bottom resistor is required in the model to fit the data. However, this model does not fit the data at stations 0W, 100W or 300W very well although the general model response is adequate. This is likely due to inaccuracies in positioning of either the loop or the stations or both causing inaccuracies in the modeling and inversion process. For these stations, the model, *MultLoc_MI5 model* decays too quickly after Ch5 but then comes back in to fit the data around Chn13. There is insufficient data to explore this issue further.

Central Station Model: The model for only the most interior calibration point which also explores the lowest possible resistivity of the cover layer is:

MI5 Model:

27 Ωm – 18m, 5.5 Ωm – 18m, 6 Ωm – 21m, 5.7 Ωm – 30m, 7.8 Ωm

The fact that the model for the interior calibration points is not sensitive to the bottom receiver is entirely expected as the data for interior points is not normally sensitive to resistivities at depth.

AEM Model for Site 3:

Using the model - *MultLoc_MI5 model* **-** as a starting model for inversion of the airborne data, a suitable model for the airborne stations was determined as:

MI5_Site3.

142 Ωm – 34 m, 5 Ωm – 13m, 20 Ωm – 19m, 17 Ωm

In this model, the conductive layer is considerably deeper than in the ground models. The ground models when simulated for the airborne system produces much too large a response for the synthetic AEM data particularly at early to early mid-times.

XTAL data

Data was collected on an EW line at 500W, 400W, 300W, 100W, 0W, 100E, and 300E with the same system settings as for the REF data.

There are problems determining which data belongs to which point due to the method of assigning coordinates to the stations in the data files and lack of complete reporting by the survey operator. Additionally, the proper locations of data for stations that we thought obvious have inconsistencies in the data with respect to their assigned location. It is thought that possibly data was collected in a different order than reported by the operator. The only data locations for which we can be entirely sure are 100E and 300E. This data at both stations agrees reasonably with the centre point REF model upon inversion.

100E model:

32 Ωm – 22m, 4.6 Ωm – 15m, 5.2 Ωm – 20m, 5.9 Ωm – 31m, 7.2 Ωm

This model, determined from 100E, fits 300E reasonably well but the best model for 300E has the depth to conductor at 18.5m as the best model.

Comments on AEM Model vs. Ground Model for Site 3

AEM model: MI5_Site3.

142 Ωm – 34 m, 5 Ωm – 13m, 20 Ωm – 19m, 17 Ωm

Ground model: MultLoc_MI5 model

145 Ωm – 11m, 3 Ωm – 3.3m, 6.5Ωm – 60m, 7Ωm – 60m, 17.3 Ωm

Ground model: 100E.

32 Ωm – 22m, 4.6 Ωm – 15m, 5.2 Ωm – 20m, 5.9 Ωm – 31m, 7.2 Ωm

The AEM model has a significantly thicker resistive cover and returns to a moderate resistor at quite a shallow depth. Once again, a possibility is that the AEM data was collected at a higher elevation than recorded.

But, as it stands, depth to the conductive material below the more resistive cover is 12-16m too deep for the AEM data. The AEM model was derived principally from L20670 which is immediately to the west of the loop. Also, we utilized primarily data from the northern edge of the loop to several hundred metres south of the loop. This was due to there being a significant variation in the AEM response north of loop starting at a few hundred metres north of the loop.

L20660 which is east of the loop has a reasonably comparable model to the ground model whereas L20670 near the loop and L20680 to the west of the loop do not. This issue points to a significant problem with the airborne inversions. That problem is that there was too much variation in the shallow resistivity model from line to line which was unexpected from this geology. The ground data does not indicate such variations in shallow resistivity which points again to amplitude problems in the AEM data.

On Lines 20660, 20670 which are slightly east and near the loop respectively, the ground model synthetic response to the AEM system is almost an exact DC shift of 2.3 when compared to the AEM data. That is, if the AEM data at all time channels were increased by a factor of 2.3 then AEM data near the loop fits the ground model for these two lines! This would imply that the altitude is not the issue but rather the amplitude of the data is shifted. This could happen for example if the current in the loop was reduced by 2.3 over this section of the survey. Tilts of the transmitter and receiver could not explain this amplitude shift. Other possibilities are in the processing of the data.

Site Conclusions: The main conclusions from this site are

a) Again, the area appears to consist of a more resistive cover of moderate thickness of about 10-15m.
b) The strata below that is significantly more conductive as at the other sites.
c) The more conductive strata persists to some depth of at least 120m. Resolution of the exact thickness of these conducting strata cannot be resolved without at more comprehensive ground survey
d) The AEM data does not agree with the ground data. There does appear to be am amplitude problem .

6.5 Site 6: November 29, 2011

For this the first site surveyed, the originally planned 400x400m loop was used. However, it took too long for the crew to put out the loop and retrieve it at the end of the day and thus the loops were reduced in size for the later sites. On this day, in addition, variations on the system parameters, the use of transmitter and receiver coil were also attempted.

Reference Mode Data – 30Hz, 100sq.m coil, EM57 transmitter

2 stations were collected at the NW corner just inside the loop. The inversion models of the 2 sites are quite close and so both points were inverted together as a 2 point inversion for 1 model.

***MultiLocREFcalib*: 26 Ωm – 19.5m, 2.8 Ωm – 13.6m, 42 Ωm – 10m, 6 Ωm – 28m, 9 Ωm**

The data requires resistor, conductor, resistor, conductor sequence to represent the various decays observed in the data. The data quality for the northern of the 2 points was not as good as the south point. The best model for the northern point was:

Model: MI5 S Point is the best model for this point but is not very different from the above model produced by joint inversion

23 Ωm – 19m, 3.8 Ωm – 14.6m, 10 Ωm – 14m, 6.7 Ωm – 51m, 8 Ωm

Not all resistivities are well determined. The surface resistivity is quite clear and the approximate conductance of 2^{nd} layer is known quite well and the thickness of 3^{rd} layer known relatively well as well as approximate resistivity of sequences below the resistor. This is due to the limited data availability caused by the two data points being so closely spaced to each other.

<u>XTAL Referenced Data</u>

<u>30Hz, 100sq.m data with EM57 Transmitter</u>

a) XTAL data was also measured at the calibration points but the data was badly un-synchronized and not of any use.
b) 10 stations on EW line from 800W to 300W, 100W to 100E and 300E and 1 station on NS line at 300N were also taken.

However, this latter data appears unreliable for these reasons:

a) The data appears visually to be out of synchronization as observed from the response in the last channel which is many times greater than the response in second to last channel indicating the data is actually significantly later in time then the instrument reports. This is quite common in our experience with Geonics data not carefully synchronized.
b) All of the data at the other 4 sites have similar responses whereas this XTAL data is quite different. The general response of the REF data at the calibration point agrees with the other sites
c) The model produced from the REF data at the calibration points indicates the XTAL data is out of sync by between .5 to 1 msec but the exact shift in the time channels cannot be determined.

<u>EM47 Transmitter Data:</u>

At this site, data was collected with a smaller battery powered transmitter named the EM47. The transmitter only allows data to be collected in REF mode and thus all discussions concerning EM47 data refer to data in REF mode. In addition, a smaller coil with an effective area of 31 square meters was used. This coil is categorized by the manufacturer as having higher frequency content than the 100 sq.m. coil. Two fundamental frequencies were used; 30Hz as in all the other cases and 75Hz.

Note: The data decays with this coil from a simple observation perspective has fewer features than the 100 sq.m. coil data. Thus, we infer from simple observation that the data has less resolution implying less frequency content.

<u>75Hz data</u>

Data was collected at only 2 points, 300E outside the loop and 100E (2 repeats) inside the loop. At the interior point, 100E, the *MI 5 S Point* model fits very well from about .5msec to the last channel at about 2.6msec. However, both data points indicate that the time channels of the data are actually about .25msec later than understood from the instrument. This conclusion is based upon the assumption that the REF model produced from the EM57 data is reasonably correct.

Further, if we invert the data as it is provided with the timing of the channels as provided by the data file then the models for 100E and 300E are completely inconsistent which is unlikely from the perspectives of the geology and the EM57 data. The 100E data indicates there can be no resistor at the surface but rather the surface resistivity is about 3Ohm-m which is completely different than the calibration model or the models from any of the other sites. On the other hand, the inversion of the 300E point only provides a somewhat similar surface resistivity to the calibration model and other sites. These results imply that the 75Hz XTAL data is not of use particularly inside the loop. This is disconcerting as the manufacturer recommends inside loop data for this transmitter at this base frequency.

30Hz Data

The same 2 points were collected as for the 75Hz data but there were no repeats. Again the 31 sq.m. coil was used with the EM47 Tx.

- The inversion models for the inside and outside points are much more similar for the two stations than for the 75Hz data
- The calibration model for the EM57 data fits the inside station much better than for the 75Hz data. However, there is a DC shift observed between the data and the simulated response of the calibration station model for the EM57 data. Ch7 to the last channel have a DC shift of approximately 0.92 implying a possibility that the TX is only putting out .92 Amps rather than the stated 1Amp. Note, the instrument is fixed to output 1Amp but this may be nominal.
- The early time data at 100E does not have the early time curvature that we would expect from the EM57 model. A time shift does not appear to be the answer to this inconsistency although a slight time shift and a DC shift would make things closer. It does not appear to be a bandwidth issue either as the use of much higher frequencies in the simulation does not affect the simulation of the early channels. This is not unexpected due to the relatively low resistivities. Bringing the upper bandwidth down produces an increased curvature in the early time of the opposite shape than the data at the inside station and does not help fitting the outside point.
- However, both sites produce a relatively thick resistor in the inversions lying over a quite conducting layer much like the REF model with a resistor below with comparable values to the REF model at the calibration sites.

MI5 EM47: best model inside the loop

103 Ωm – 33m, 2 Ωm – 10m, 2.8 Ωm – 8m, 12 Ωm – 70m, 7 Ωm

For comparison

MI5 S Point: from the REF EM57 data

23 Ωm – 19m, 3.8 Ωm – 14.6m, 10 Ωm – 14m, 6.7 Ωm – 51m, 8 Ωm

The top resistivity in *MI5_EM47* could be adjusted down to more closely agree with the EM57 REF model. However, this works well at the inside point but is very bad for fitting the outside data. Otherwise, the REF model has a 15m thick conductor while the EM47 model has an 18m conductor sequence. In both models a resistive layer is determined at depth. Detailed resolution of the depth of this resistor is not expected from either of these datasets due to the limited quantity of data sites.

In this case, we have data from two different coil sensors which do not appear to agree. This is an experience we have noted with other equipment of this type.

AEM Model for Site 6:

Generally, the 2 ground models *MI5 S Point* and *MI5 EM47* show reasonable comparison to the AEM data in the vicinity of Site 6. Also, the AEM inversions show a reasonably consistent model for the ground over the ground survey area.

There are various models which fit the AEM data. This is normal considering the nature of the geometry of the AeroTEM system, the height of the measurements and what we observe of the resistivity structure from the ground data. However, using *MI5 EM47* as a starting model produced reasonable smooth and comparable results on the two lines just east and just west of the loop over NS distances of about 800m. The resulting inversions were a resistive layer on top (20-40 Ωm) of between 25-35m thickness followed by 2 thin conducting layers, a more resistive layer of about 20 Ωm and thickness of about 60m and then a conductive layer at bottom of about 5 Ωm.

Discrimination between the two conductive layers (layer 2 and 3) could not be done and so were merged these layers. Resistivity of top layer could vary and so was restricted to a maximum of 30 Ωm and a minimum of 19

Ωm in accordance with the ground models for this site. Similar comments can be made for layer 3 (resistive layer) and finally the conductive basement is required but is not well constrained so was set to have a minimum of 3 Ωm.

These constraints produced a model for the 500 metres north-south from the centre of the loop on the east AEM line of

East Line MI4**: 19 Ωm – 28m, 3.7 Ωm – 11m, 23 Ωm – 70m, 7 Ωm**

And on the west line a model

West Line MI4**: 25 Ωm – 35m, 3.0 Ωm – 11m, 24 Ωm – 68m, 5 Ωm**

These models are very comparable but the variation in the surface resistivity is a representation of the early time amplitude increase which generally appears on the east line as compared to the western line all along that particular flight.

We compare these models to the ground model

MI5 S Point**:**

23 Ωm – 19m, 3.8 Ωm – 14.6m, 10 Ωm – 14m, 6.7 Ωm – 51m, 8 Ωm

The top layer is significantly thinner for the ground data and the conductive layer somewhat thicker. Plus, the third layer in the AEM model is more resistive as compared to the ground model and the 4th conductive zone shallower. All of these results are not unexpected since if we apply the ground model to the airborne data, then the simulated response of the AEM data is too high as observed previously.

Applying the airborne eastern line model (more conductive) to the ground data at the calibration point produces a comparable decay. A DC shift of 1.32 to the AEM produced not a bad fit to the ground model.

Again, we appear to have a small amplitude problem with the AEM data. All of the test sites indicate relatively uniform resistivity structures on the scale of the AEM line spacing. However, the AEM inversions suffered from lack of uniformity line to line. These results indicate a likely possibility is that there are inaccuracies of the AEM data amplitudes of the order of 30 to 50 percent. This issue is more critical in the early time data.

<u>Site Conclusions:</u> The main conclusions from this site are

a) The area appears to consist of a more resistive cover of moderate thickness of about 20m.
b) The strata below that is significantly more conductive as at the other sites.
c) The more conductive strata persists to some depth of at least 100m. Resolution of the exact thickness of these conducting strata cannot be resolved without at more comprehensive ground survey
d) The AEM data does not agree with the ground data. There does appear to be am amplitude problem .

7. Final Comments on 2011 AEM Inversions and 2011 AEM Data Quality

Inversions performed in 2011 generally show the correct approximate structure. However, from the ground results, we now realize that the later time data is quite reliable and the 1st channel is not as bad as we thought in 2011 but still does not appear as accurate as the other early time channels. Knowing from the ground data that no resistive layer at depth can be determined and the knowledge that there are roughly 4 different strata of only slightly different resistivity, we would have sought a different type of model for the 2011 inversions which may have provided discrimination in the top 2 layers. But, without *a priori* knowledge that such layers existed, we could not determine from the AEM data alone that these layers existed. Because of the geometry of the airborne system with the receiver inside the transmitter loop combined with the height of the instrument and the conductivity of the geology and subtle variations in the strata below the top resistive stratum, there was no obvious reason to pick a more complicated model structure.

There appears from the ground data confirmation that there are amplitude problems in the AEM data.

8. Conclusions

First, the ground data surveys were sufficient to demonstrate that the resistivities of the ground at least to depths of 150 to 200m were varying laterally very slowly. Thus, the use of the airborne surveys with line spacings of the order of 500 to 1000m are suitable for imaging the resistivity structure to these depths. In addition, the use of a one dimensional technique which stacks resistivities along a survey line for imaging is also appropriate. However, we would recommend multipoint airborne inversions. That is, we would recommend the use of a moving window containing data from several datapoints be used to invert airborne data. Secondly, spatial smoothing constraints should be applied to the inversions both inline (along the profile) and if possible, crossline (between profiles).

As the earth obviously consists of several different strata, we would not suggest an overparametrized inversion such in the so-called Occam technique but rather an underparametrized inversion where each distinct strata was represented uniquely in the inversion process. This would require preliminary ground data as generally the airborne data is subject to multiple model types which can fit the data and thus the strata must be known to exist *a priori*.

The ground survey met many of the objectives of this survey but not all. Obtaining the planned survey of 400m by 400m loops with two orthogonal 1km profiles lines crossing through the loop would have provided all the information required. From the airborne survey, it was our opinion that it was likely such a survey should be performed at each site. From the analyses of the data collected, we can now state for certain that such a survey would be optimal.

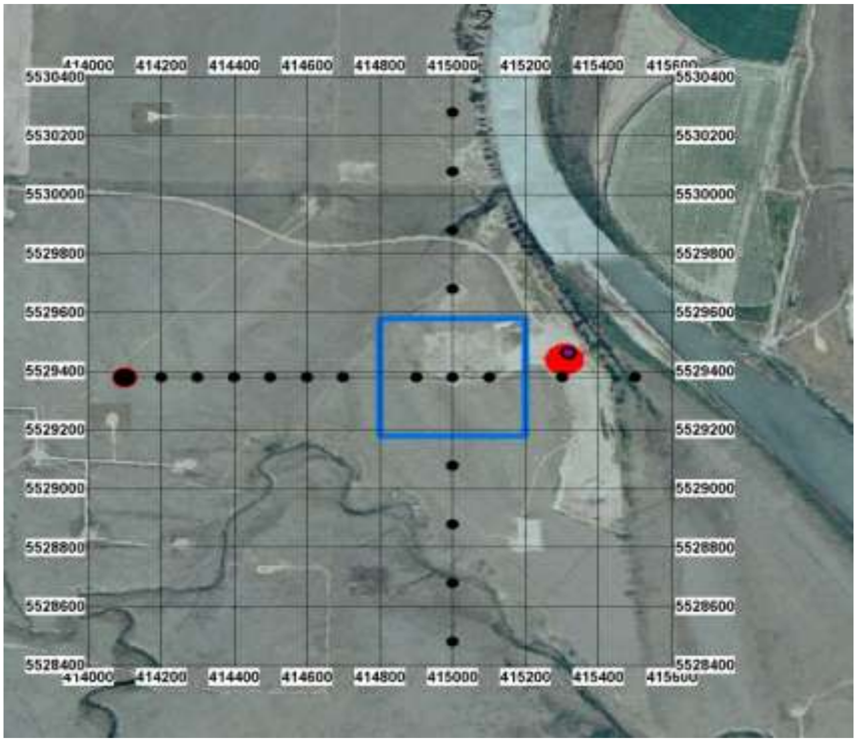
The ground survey was able to detect the resistivity strata to depths between 150 and 200m depending on the data collected at the particular site and the conductance of the sub-strata. In all cases, the ground is topped by a more resistive strata than the strata below. There is strong evidence for a significantly conductive strata just below the cover material at all sights. Given that it is assumed that there is no ground water table immediately below the resistive cover of some tens of meters, this immediate substrata must contain significant shale or clay materials and moisture must be trapped in this strata. Clay or shale cannot reach this type of resistivity (3-5 ohm-m) without moisture content. Below, this conductive strata are more strata of lower resistivities than the cover but higher than the strata immediately below the strata. The resistivities of these strata imply shale or clay-bearing strata with some but not high moisture content. There is evidence at some sites of a further resistive strata below of a few tens of ohm-metres. A larger loop and a large survey would be required to resolve this strata.

Unfortunately, the survey does strongly suggest that there are problems with some of the airborne data. The problems are twofold,. The first being that there are amplitude problems with some of the data. That is, the decays are correct but the entire decay must be increased or decreased uniformly for all data channels and although long lengths of a profile. Secondly, there are sometimes decay issues and thus there suggests that an intrinsic coil decay is present in some of the data. More elaborate calibration of the system would be required to determine this. However, this problem is likely instrument dependent and such calibration is not likely useful after the survey is complete.

We strongly recommend for future surveys that a calibration site be prepared which allows the airborne system to be tested just prior to the beginning of a survey and if possible several times throughout the survey. This calibration site should have several ground systems used to survey it and drill results also be available.

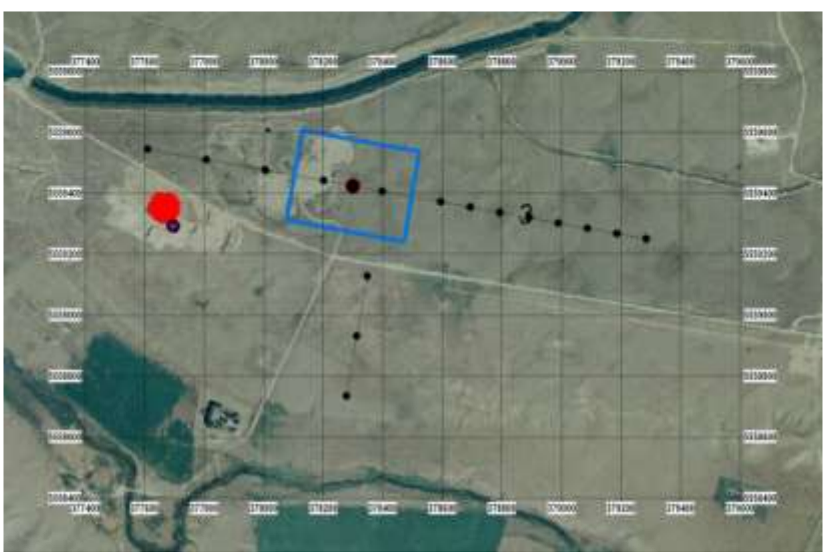
Appendix I: Survey Plans for Each Site

Site 2: Figure 2 shows the survey plans for Site 2. Loop is shown in solid blue and stations by black dots.



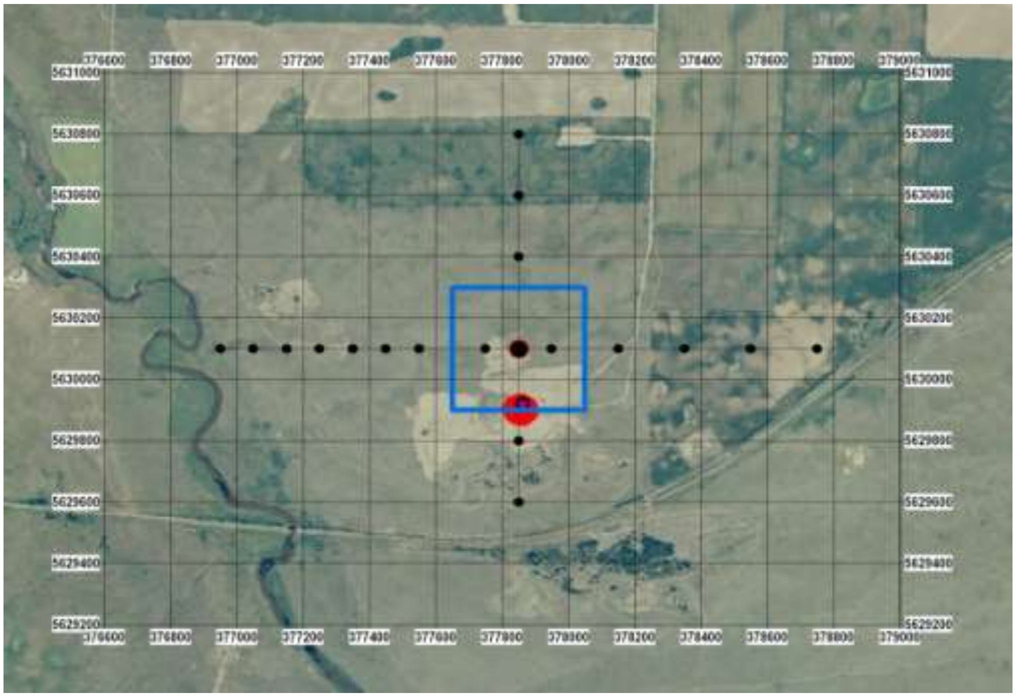
NAD83: 415000, 5529380

Site3: Figure 3 shows the survey plans for Site3. Loop is shown in solid blue and stations by black dots.



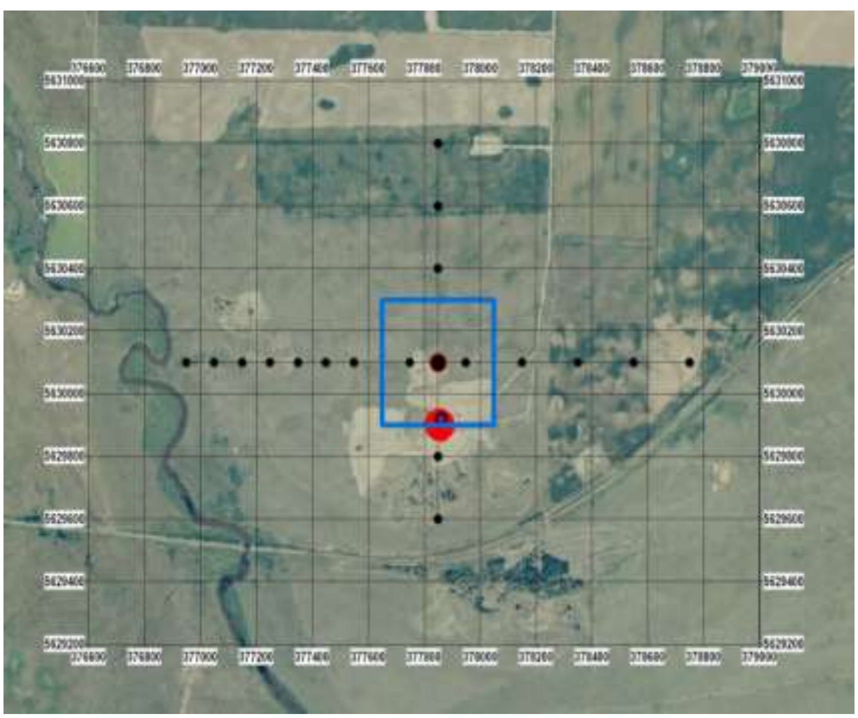
NAD83: 378300, 5559425

Site 4: Figure 4 shows the survey plans for Site 4. Loop is shown in solid blue and stations by black dots.



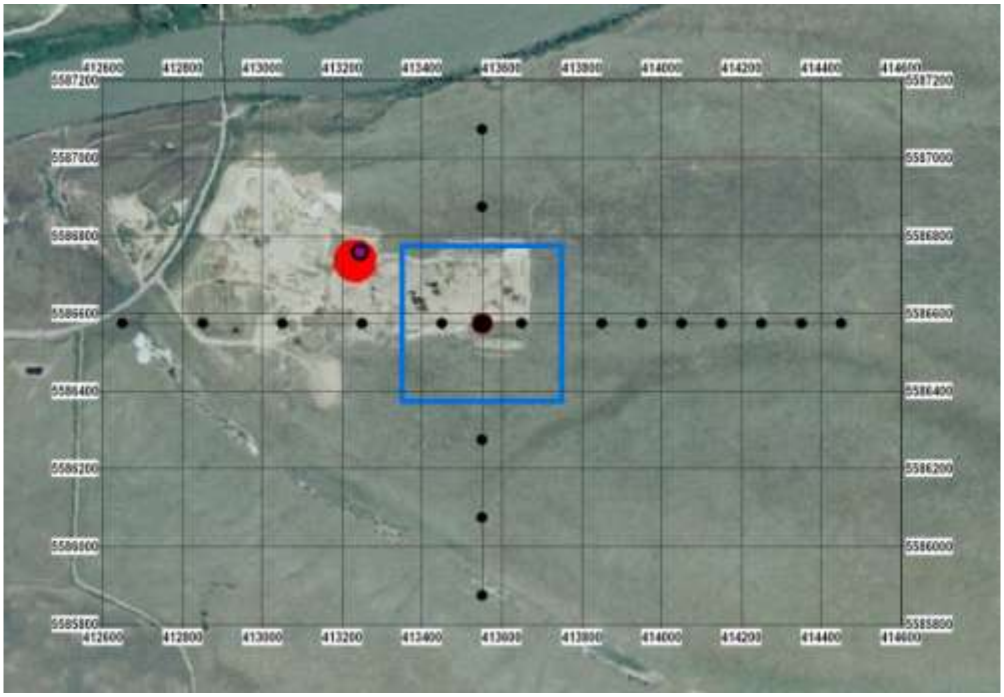
NAD83: 377850, 5630100

Site 4: Figure 4 shows the survey plans for Site 4. Loop is shown in solid blue and stations by black dots.



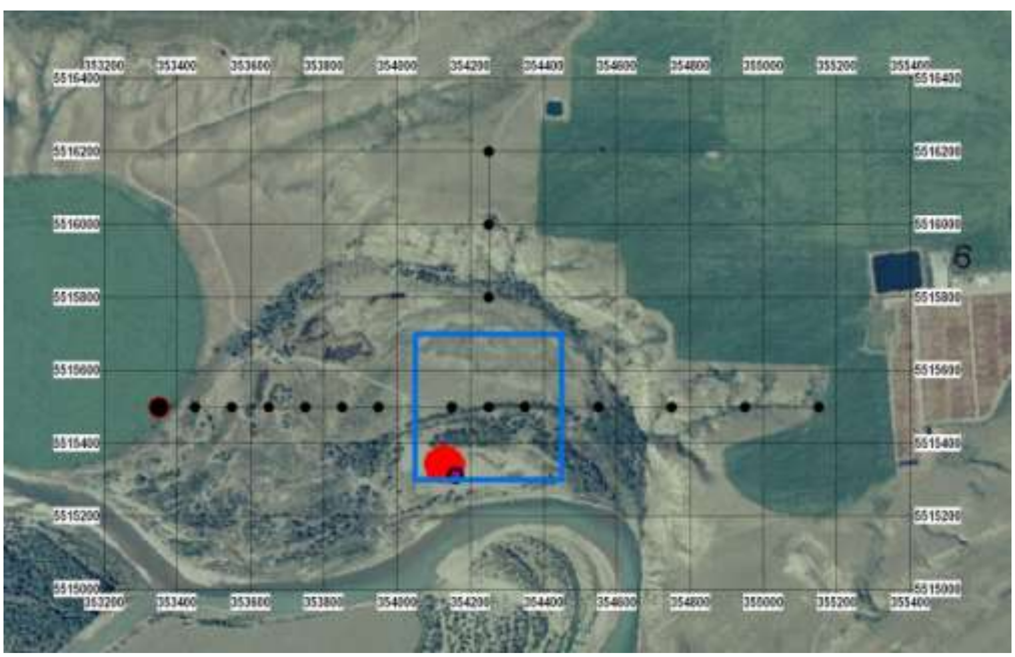
NAD83: 377850, 5630100

Site 5: Figure 5 shows the survey plans for Site 5. Loop is shown in solid blue and stations by black dots.



NAD83: 413550, 5586575

Site 6 Figure 6 shows the survey plans for Site 6. Loop is shown in solid blue and stations by black dots.



NAD83: 354250, 5515500

Appendix II Model fits to Data – An Example

This is certainly not a comprehensive showing of all the model fits to data that were explored. It is rather presented to illustrate the level of accuracy of model fits to data that were generally required in the analyses.

Site 5

First, we show the fit of the reference data to the preferred model for this data. The Reference data fit to model *centre_ref2_nobase* is shown. Data is shown in red and the synthetic data produced by the model in blue. Surface resistor and sub-strata conductor are obvious in the decay of the data.

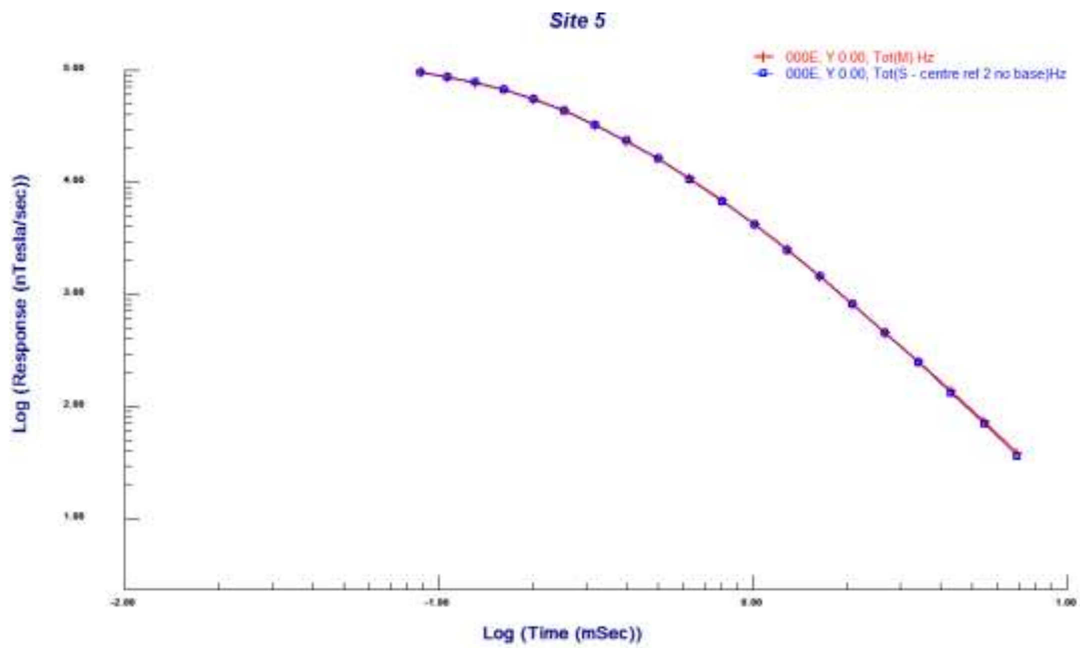


Figure 7: Data Fit of Site 5 inside loop REF data to model – log time vs log amplitude is shown.

Now for the crystal referenced data, we show the fit to an inside and an outside station for the joint inversion model – *MultiLoc2_MarqInv_5*.

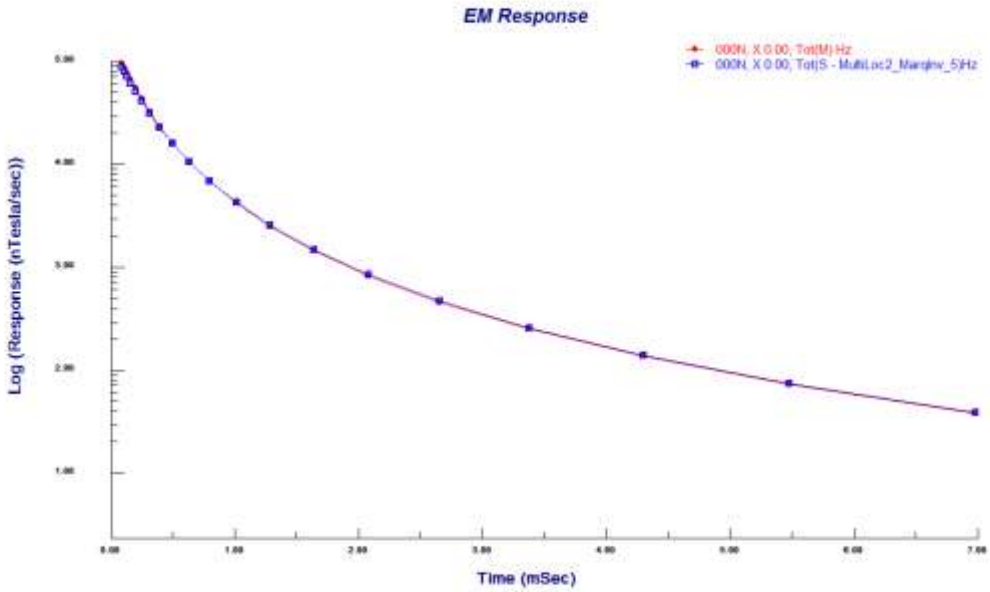


Figure 8: Data Fit for Inside Loop XTAL data to model. Data in red and model in blue. Linear time to log amplitude is shown.

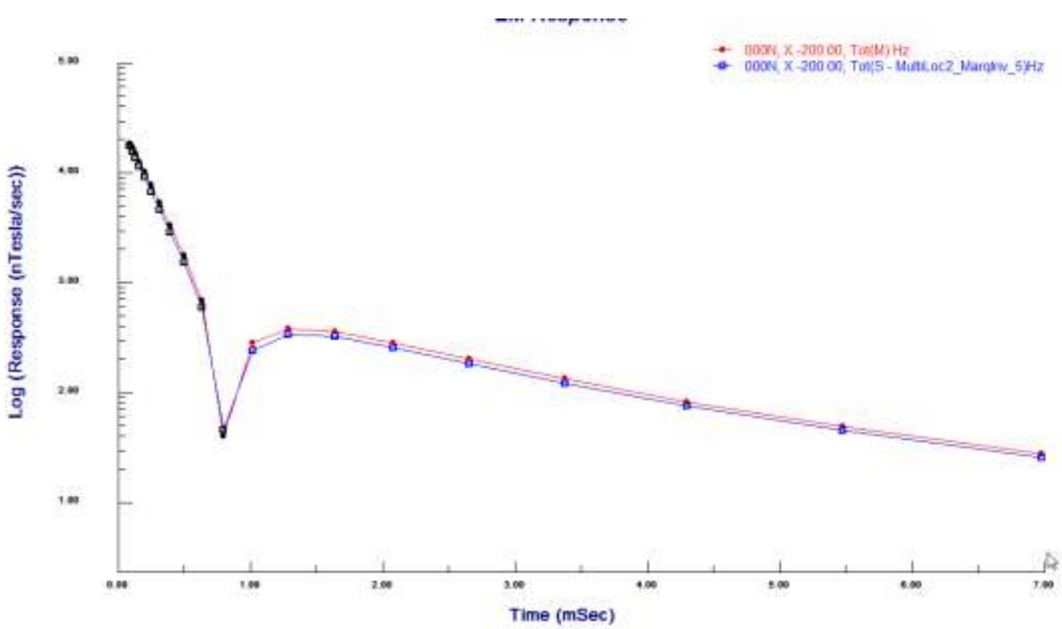


Figure 9: Model *MultiLoc2_MarqInv_5* fit to data an 200W outside the loop. Linear time vs. log data amplitude is shown. Negatives are shown via black symbols.

Note: For those unfamiliar to fitting outside loop data, the position of the sign crossover is critical as it indicates the diffusion of currents past the data station and thus is very specific and accurate in the resolution of the ground resistivities at depths depending on the distance of the site from the loop. The late time decays indicate the rate of diffusion past the site and thus represents the average resistivity at depth.

Site 5 AEM data (red) fit vs AEM model (*Site 5 AEM)* (green) versus the ground model, *MultLoc2_MarqInv_5,* blue. This plot shows clearly that the ground model indicates a shallower conductor than the airborne data but eventually at the depth, the two systems image approximately the same resistivity.

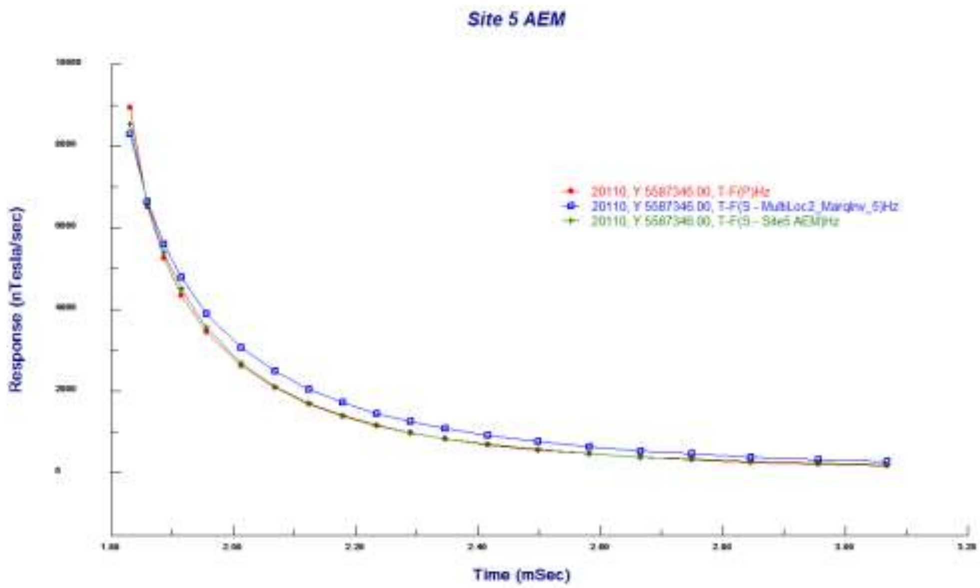


Figure 10: AEM data at Site 5 vs. synthetic data for AEM model and ground model.