A comparison of airborne and ground electromagnetic data near the Grand Canyon

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Summary

In 2007, three time-domain electromagnetic (TEM) airborne surveys were flown for Uranium One in northern Arizona over thick, generally flat-lying sedimentary sequences. Each survey was flown with a different system (MegaTEM, GeoTEM, and VTEM), and data was also collected with each system over a test area for calibration. Ground TEM data was later collected at this site in 2008. The availability of data from three airborne TEM surveys at the test area allows for a unique opportunity for a comparison between these systems and with TEM ground methods. The purpose of our study was to determine whether a single 1D model could be found that is consistent with all of the EM data available at the test area and geological data, as well as to understand the differences in resolution between the different systems.

Introduction

Airborne TEM is a popular geophysical method in mineral exploration, allowing large areas to be surveyed. The data is typically mapped to identify anomalies of interest, and modeling and inversions may be utilized to understand the response. Ground geophysics is used to develop a better understanding of the structure. A model that fits the airborne data can be compared with ground results to see if they agree, and attempt to determine the reason for any differences. While the ground and airborne surveys differ in their resolution, the general structure that they find should be consistent. The collection of airborne data is complicated by the movement of the plane, and it is important to have confidence that what is seen on the ground is actually what is being measured in the air.

Several different airborne TEM systems exist, including fixed-wing systems such as MegaTEM and GeoTEM (Fugro Airborne Surveys), and helicopter systems such as VTEM (Geotech Ltd.) and AeroTEM (Aeroquest) with in-loop receivers but there are few studies to determine the quantitative differences between these when mapping sedimentary environments.

Geologic Setting

The test site is located on the so-called North Rim some distance from the Grand Canyon, an area that is actively being explored for breccia pipe uranium deposits. The host environment for the breccia pipes is a sequence of sedimentary rocks including limestones, sandstones, and shales. At the surface is the Moenkopi Formation, comprised of sandstone and siltstone. Below the Moenkopi are the Kaibab Limestone and Toroweap Formation, which include limestone, sandstone, and gypsum. The Coconino Sandstone, which is quite thin at the test site, and the Hermit Shale underlie these. Below the Hermit Shale is a series of formations known as the Supai Group, the uppermost of these formations being the Esplanade Sandstone.

Information on the geology of the area is available from site work by Uranium One just south of the test area. Drill logs extend into the Hermit Shale.

Electromagnetic Data

The following data were collected at the test site:

Ground Data:

1. Fixed Loop TEM collected with a Protem system using a TEM67 transmitter (Geonics) in May 2008. 400 m x 400 m loop, centered at (750E, 5200N). Data was collected on two north-south lines (650E and 750E) between 2900N and 6000N at 100 m station spacing. Base frequency was 30 Hz, and all three components were collected.
2. Fixed Loop TEM collected with ZeroTEM (Zonge) in May 2008. Same loop as the first survey. Base frequency was 16 Hz. Data was collected only between 5100N and 5800N on Line 650E.

Airborne Data:

1. MegaTEM (Fugro) in February 2007. Base frequency of 30 Hz. Three components. The data was later windowed to have 20 off-time channels rather than the 5 on-time and 15 off-time typically provided. North-south lines at 100 m line spacing. In the vicinity of the test area, the lines are at about 600E, 700E, and 780E, and extend north to about 4900N.
2. GeoTEM (Fugro) in February 2007. Base frequency of 30 Hz, and 20 off-time channels. North-south lines with 100 m line spacing. Two lines are at approximately the same eastings as the Geonics lines (640E and 740E).
3. VTEM (GeoTech) in May 2007. Only Hz collected. 28 off-time channels. North-south lines with a line spacing of 100 m. The lines are at approximately the same easting as the MegaTEM lines near the test site (590E, 690E, 790E).

In addition, Max-Min data was collected just 100m south of the calibration area at several frequencies and two separations. VLF-R data was also collected at this site at two polarizations. Several holes were later drilled in the center of these surveys.

Comparison of ground and airborne TEM

Method

EMIGMA V8.1 (PetRos EiKon, 2009) was used for layered earth modeling and 1D inversion (Jia *et al*, 2005, Jia *et al*, 2007). Comparison was performed using the steps outlined below:

1. Development of a layered earth model for the Protem (Geonics) ground data. A model was developed using a 1D multi-station inversion in which the best model 1D model for several stations was found. This has the advantage over single-station 1D inversions to provide the best overall model. Particular attention was paid to both Hx and Hz, including any variation across the survey area, though the ground TEM indicates that the geology is fairly uniform laterally.
2. Simulation of the Protem ground model for the Zonge system (ZeroTEM) and comparison with the Zonge data.
3. Simulation of the ground model for the MegaTEM, GeoTEM, and VTEM data and comparison to the airborne data. Finally, a detailed assessment of the differences between the ground model and the best models for the airborne data was performed.

Ground Data Results

Geonics Fixed Loop TEM

Preliminary modeling resulted in the development of a four-layer model that has a similar response to the measured data. This model was used as the starting model for a four-layer Marquardt inversion on Hz of the 11 south-most points on Line 650E (1300-2300m south of the loop centre and just off-centre of the loop). The result is Model4S (Table 1), which fits the data well across the entire survey (Figure 1). The fact that a single layered resistivity model can be found to generally match the response verifies that the subsurface structure is almost uniform across the survey area and provides an unusual sample for these studies. Modeling and inversion work was performed with a 17 kHz bandwidth for the receiver. The instrument manufacturer has not responded to queries as to the actual bandwidth of the instrument.

In Table 1, the resistivity structure of Model 4S is correlated with the background geology. The top layer of 123 Ωm is assumed to be the Moenkopi due to the low resistivity. This resistivity is too low for the limestone-dominated Kaibab and Toroweap, since at other sites in the region where the Moenkopi is absent, EM data shows that there is a much higher resistivity at surface. Both VLF-R and high-frequency Max-Min also have apparent resistivities of about 120 Ωm. Since these methods are not sensitive to deep structure, the apparent resistivity that they detect should be close to the resistivity of the Moenkopi. The Protem data is in agreement with the results of these surveys. The thickness of the Moenkopi in the model (40 m) also generally agrees with the thickness of the Moenkopi in the drill cores to the south, where it is 40-50 m thick (46 m average).

The resistive layer below the Moenkopi is the Kaibab and Toroweap. Additional modeling found that these formations cannot be individually distinguished using the EM methods. The 40 Ωm layer starting at 263 m depth is a combination of the Coconino and Hermit, which also cannot be differentiated at these depths. The Coconino is expected to be quite conducting due to saline fluids, but is very thin (about 2 m thick from drill results) in this area. The depth to the top of the Coconino is 260-280 m in drill cores to the south, so the model is in agreement with drill results. The bottom layer is assumed to be the Supai Group (sandstones and siltstones). The drill holes extended only into the Hermit.

Table 1: Model 4S

Resistivity (Ωm)	Thickness (m)	Depth to Bottom (m)	Lithology
123	40	-40	Moenkopi
330	223	-263	Kaibab/Toroweap
40	260	-523	Coconino/Hermit
160			Supai Group

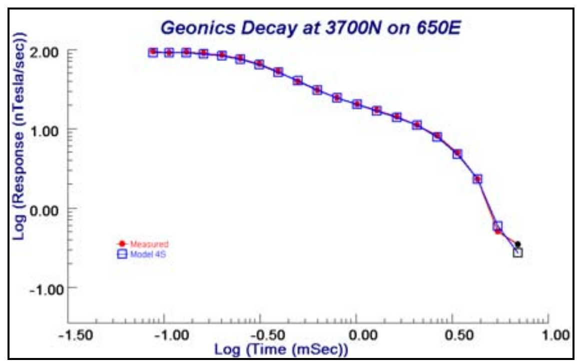

Figure 1: Hz decay at 3700N on Line 650E in the Protem ground data. Red is the measured data. Blue is the response of Model 4S.

All four layers in Model 4S are necessary to fit the ground response. However, at short separations, particularly inside the loop, the system is not very sensitive to the resistivity of the fourth layer, or even its existence. For example, if the resistivity of the bottom layer is increased from 160 Ωm to 1000 Ωm, this makes little difference to the in-loop model response, but has an increasingly larger effect is seen due to the bottom structure when moving away from the loop. If the bottom two layers are replaced by a single layer of 30 Ωm, the curvature of the decay of this model does not fit the response to the south, but fits the in-loop response very well, except at the last two channels which are questionable. A three-layer Marquardt inversion (not multi-station) in which only the top three layers are in the starting model has good results in-loop but not outside the loop, particularly at large separations. Conversely, a 3-layer inversion where only the bottom three layers are in the starting model does not fit the data as well but it is most apparent at early channels inside the loop. This demonstrates the usefulness of in-loop and out-of-loop data for determining background resistivity structure.

The discussion on the ground data thus far has focused on Hz, but Hx and Hy were also collected. Model 4S fits Hx well, though Hx is generally noisier away from the loop. Due to the manner in which Hy was collected, the data is not of sufficient quality for interpretation.

While Model 4S fits the data well across the survey, it was noted that near the center of the loop, the response is slightly too low at mid-late times. Decreasing the thickness of the resistive layer by 10 m improves the fit (Model 4N). A close inspection of the measured data versus the response of Model 4S and Model 4N shows that there is not a gradual thinning of the resistive layer towards the north, but rather a sudden change between 4300N and 4400N on 650E and 4200N and 4300N on 750E in Hz (Figure 2), possibly indicating a fault. Thus, this ground data seems to provide high resolution of somewhat subtler deep structure. This apparent fault corresponds at surface to a wash at about 4400N, as seen in the digital terrain model.

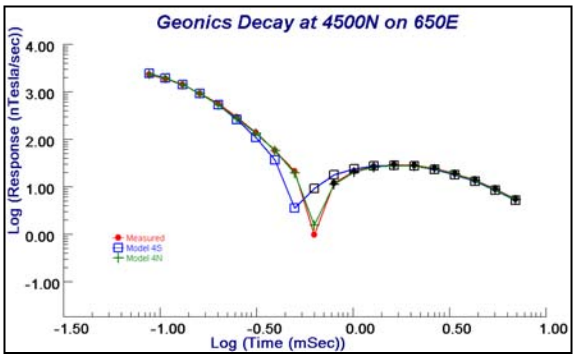

Figure 2: Hz decay at 4500N on Line 650E in the Protem ground data. Red is the measured data. Blue is the response of Model 4S, and green is the response of Model 4N.

Zonge Fixed Loop TEM

Because the Zonge system does not monitor the pulse, unlike the Protem system, some adjustments needed to be made to the nominal system settings before modeling. Once these adjustments were made, Model 4N (which fits the Protem ground data at the north end of the survey), fits the Zonge data well.

Airborne Results

MegaTEM (Fugro Airborne)

Model 4S was simulated for the MegaTEM data over the calibration test area after careful checking pulse width, dipole moment and window positions. Initially, we utilized an upper bandwidth of 17 kHz. Although Model 4S matches the MegaTEM data at mid-late times reasonably well, the response of the model has too high at the first time channel and too low at subsequent early channels (Figure 3). The MegaTEM data also shows a variation in response from north to south over the calibration site that was not observed in the Protem data. From 4200N to the north end of the survey, the early-time response is fairly constant whereas the early-time response continually increases from 4200N to the south end of the calibration site.

The initial simulation of Model 4S for the MegaTEM was performed using a bandwidth of 17 kHz for the system with a low-pass filter applied. If a bandwidth of 4 kHz is used instead of 17 kHz, the Model 4S fits the MegaTEM data well to the north of 4200N where the response stays constant (Figure 3). However, after this adjustment in bandwidth the response of the model south of 4200N is slightly too small but just for the early channels. This misfit increases until it reaches a maximum at station 3000N (Figure 4). However, mid-time and late-time still fit. To adjust the model to fit the increasing amplitude of the early channels to the south end requires adding shallow conductance.

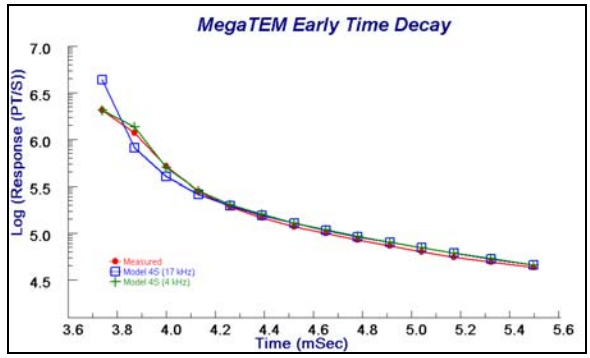

Figure 3: Early-mid time Hz decay on Line 10090 at (700E, 4812N) in the MegaTEM. Red is the measured data. Blue is the response of Model 4S for a receiver bandwidth of 17 kHz. Green is the response of Model 4S for a receiver bandwidth of 4 kHz.

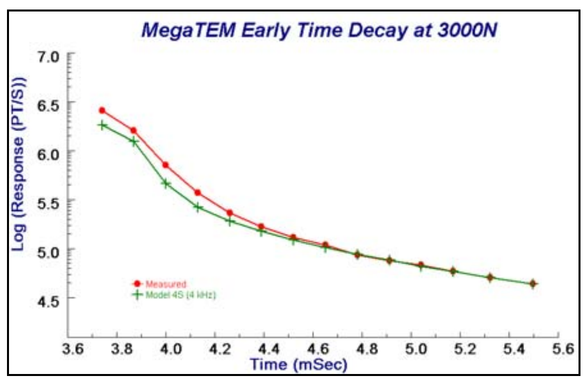

Figure 4: Early-mid time Hz decay on Line 10090 at (700E, 3003N) in the MegaTEM. Red is the measured data. Green is the response of Model 4S for a receiver bandwidth of 4 kHz.

Although Model 4S fits the MegaTEM after adjusting the bandwidth, such a 4-layer model would not have been developed by study of the MegaTEM alone. This system is not very sensitive to the model's fourth layer (Supai Group) as this set of formations is not necessary in the model to fit the curvature of the decay. A 3-layer model in which the bottom layer has a resistivity of 30 Ωm also fits the MegaTEM well. Thus, the Supai Group has an effect on the data but none of the formations below the Coconino can be discriminated.

Comparison of ground and airborne TEM

GeoTEM (Fugro Airborne)
The results for the GeoTEM are very similar to that for the MegaTEM, although the GeoTEM data is significantly noisier than the MegaTEM. As with the MegaTEM, if Model 4S is simulated for the GeoTEM with a bandwidth of 17 kHz, the response does not fit the early-time data over the entire calibration area. In the case of the GeoTEM, Model 4S best fits the data north of 4200N with a bandwidth of 6 kHz, rather than 4 kHz as in the MegaTEM. South of 4200N, an increased shallow conductivity is needed, as in the MegaTEM. An additional site some distance away for which both GeoTEM and ground data were available was also checked, and it was found that for a bandwidth of 6 kHz, the ground model would well represent the GeoTEM.

VTEM (Geotech Ltd)
Model 4S was simulated for the VTEM with a higher bandwidth of 170 kHz from our initial knowledge of the nature of the receiver coils. Initially, we used the waveform provided by the manufacturer. However, the model produced by the VTEM data was clearly wrong. Not only did it not agree with any of the ground data or the other airborne surveys but was contrary to what was known about the geology. However, we concluded that this was not simply due to the bandwidth of the system. Thus, we proceeded to experiment with adjustments to the waveform. It was discovered that with a simple adjustment to the waveform and a small shift in the position of the time channels resulted in a simulation of Model 4S that agreed with the other airborne data (Figure 5).

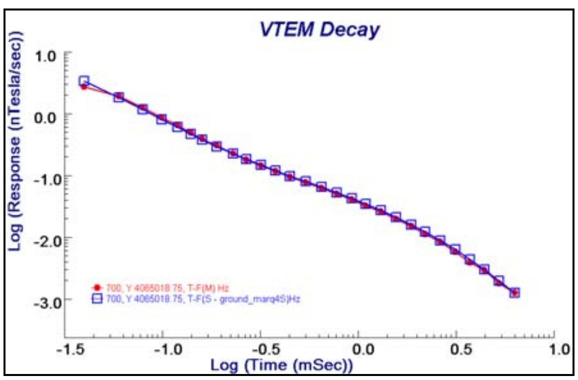

Figure 5: Decay on Line 700 at (690E, 5018N) in the VTEM, after waveform adjustments. Red is the measured data. Blue is the response of Model 4S for the initial simulation settings.

Conclusions

The GeoTEM survey was carried out over a very large region. In the vicinity of the calibration site, this data indicates a very uniform east-west response. The response is quite uniform to some distance north of the calibration site but has an increased early-time response at the south end of the calibration site for about 1km. It was striking that our ground model fit the GeoTEM data after adjusting the upper bandwidth. This was true both at the north end of the calibration site as well as several kilometers north of the site. In addition, the model fit the data well from late early-time to the very late time channels over the entire calibration site. We therefore compared ground models in other locations in this survey region with the airborne data and found that a similar adjustment to the upper bandwidth resulted in a fit of the ground model to the airborne data. This also appears true for other surveys in other regions of the world but this has not been fully confirmed. Adjusting the bandwidth of the MegaTEM models provided similar results. If we then adjust the waveform of the VTEM data, we arrive at models that are consistent for all airborne surveys including a previous test GeoTEM survey from 2006.

The resulting consistent airborne models are in agreement with the ground model except for a slight increase in surficial conductance beginning at 4200N and maximizing at the south end of the calibration site. This increased conductance could be provided by several factors: an decrease in the resistivity of the surface layer (Moenkopi), an increase in thickness of the surface layer or an additional thin conducting layer near surface with a maximum conductance of 0.25S.

A decrease in the resistivity of the surface layer is ruled out by the VLF-R and MaxMin data collected just south end of the site while an increase in the thickness of the Moenkopi is ruled out by the drill cores obtained from several drillholes 100m south. Modeling indicates that the ground data is not sensitive to a thin surficial more conductive layer at the south end of the survey with this conductance. The increased surficial conductance for the airborne models is required over the surveys areas of the VLF-R and MaxMin. Both these surveys show conclusively that this increased conductance cannot be near surface. Also, physically there is no reason for shallow decreased resistivity as there is little moisture, high temperatures and a very arid environment causing rapid evaporation of any moisture from the shallow materials. The only remaining possibility from a geological perspective is the possibility of a deeper layer of lower resistivity within the Moenkopi or at its base. This we are studying.

Overall, our results highlight the importance of accurately knowing the system parameters such as pulse width, exact window locations and waveform details for effective interpretation of airborne TEM. In addition, it can be imperative to know accurately the impulse response of the receiver coils as well as the magnetic field output of the transmitters. All of these aspects must be accurately represented in modeling and inversion algorithms.

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