Calibration of Airborne TEM Data near the Grand Canyon

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Introduction

Airborne time-domain electromagnetics (TEM) is a popular geophysical method in mineral exploration, allowing large areas to be surveyed. There are several different systems, including fixed-wing systems such as MEGATEM and GEOTEM (Fugro Airborne Surveys), and helicopter systems such as VTEM (Geotech Ltd.) and AEROTEM (Aeroquest Airborne) with in-loop receivers. However, there have been few studies examining whether airborne TEM data can be used quantitatively. Airborne TEM is typically used for qualitative purposes, usually to locate conductors.

The objective of our study is to determine if airborne TEM can to be used for quantitative interpretation in sedimentary environments by using ground TEM as the basis for calibration of the airborne data. Ground TEM has a longer history of use and modeling codes have existed for some time. First, a ground model is found. Then, the airborne response of this model is simulated and compared against the measured airborne data to see if they agree, and to attempt to determine the reason for any differences. While the ground and airborne surveys differ in their resolution, the general structure they indicate should be consistent.

Our calibration site is located near the Grand Canyon, a region that is actively being explored for breccia pipe uranium deposits. The site includes a known breccia pipe, and was an area of intensive study for Uranium One. The host environment for the breccia pipes is a relatively flat-lying sequence of sedimentary rocks including limestones, sandstones, and shales. See [1]. At the surface is the Moenkopi Formation, comprised of sandstone and siltstone. Below the Moenkopi are the Kaibab Limestone and Toroweap Formation. The Coconino Sandstone, which is quite thin at the test site, and the Hermit Shale underlie these. Below the Hermit Shale is the Esplanade Sandstone, the top formation in the Supai Group. Information on the geology of the immediate area is available from site work by Uranium One just south of the test area. Drill logs extend into the Hermit Shale.

Methods

A PROTEM system using a TEM 67 transmitter (Geonics) was used to collect a fixed loop TEM survey on two north-south lines, 100 m apart. The base frequency was 30 Hz and three components were collected. Later, data were collected at several stations inside and near the loop with a ZeroTEM (Zonge) system. In addition, MaxMin data were collected just 100m south of the calibration area at several frequencies and two separations. VLF-R data were also collected at this site at two polarizations.

Airborne data were collected using MEGATEM, GEOTEM, and VTEM systems in 2007. The Fugro data initially had 5 on-time channels and 15 off-time channels, but were rewindowed to have 20 off-time channels to improve shallow resolution. The VTEM data contained 28 off-time channels. Although three components were collected for the Fugro data, only the z-component will be discussed here. The z-component data is of better quality in the Fugro data, and was the only component collected with the VTEM system.

Two GEOTEM lines were located at approximately the same eastings as the ground lines. The nearest MEGATEM and VTEM lines to the ground survey were roughly in the middle of the two ground lines. These are the lines referred to in this report.

EMIGMA V8.1 (PetRos EiKon, 2009) was used for layered earth modeling and 1D inversion. See [2] and, [3]. Calibration of the airborne data was performed using the steps outlined below:

1. Development of a layered earth model for the PROTEM data using a 1D multi-station inversion.
2. Comparison of the PROTEM model with drilling results.

3. Simulation of the PROTEM ground model response for the ZeroTEM system and comparison with the ZeroTEM data.
4. Simulation of the ground model response for the MEGATEM, GEOTEM, and VTEM systems to determine if the ground data are consistent with the airborne data. Waveform files were used to determine the correct airborne system parameters where possible.
5. Assessment of any discrepancies between the ground and airborne data, and analyses, if possible.

Ground Results

Geonics Fixed Loop TEM
Preliminary modeling resulted in the development of a four-layer model that was used as the starting model for a four-layer Marquardt inversion on Hz of the 11 south-most stations on Line 650E (1300-2300m south of the loop centre and 100 m off-centre of the loop). The result is Model 4S, which fits both Hz and Hx well across the entire survey. Hy was not of sufficient quality for interpretation. 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 resistivity structure of Model 4S was then correlated with the background geology. The top layer of 123 Ωm is assumed to be the Moenkopi due to its 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 indicate 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 approximately the resistivity of the Moenkopi. 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 on average 46 m thick.

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. The Coconino is expected to be quite conducting due to saline fluids. Although it is very thin (about 2 m thick based on the drill results) in this area, with the expected high conductance of saline fluids, we should have been able to resolve it based on our modeling tests. Because we cannot resolve the Coconino, we suspect that the formation is not as rich in saline fluids as expected. The depth to the top of the Coconino is 260-280 m in drill cores to the south, so the depth in the model is in agreement with drill results. The bottom layer in the model is assumed to be the Supai Group (sandstones and siltstones). The drill holes extended only into the Hermit.

All four layers in Model 4S are necessary to explain the decays in the ground data. However, at short separations and inside the loop, the system is not particularly sensitive to the fourth layer. A three-layer, single-station Marquardt inversion 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 three-layer inversion where only the bottom three layers are in the starting model does not fit the data as well as Model 4S 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.

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 4S fits the Zonge data well.

Airborne Results

MEGATEM (Fugro Airborne)
Model 4S was simulated for the MEGATEM data over the calibration test area after carefully checking pulse width, dipole moment, transmitter-receiver separation and window positions using the waveform file for the flight over the calibration site. A half-sine pulse was used to represent the current waveform.

If an upper bandwidth of 4 kHz is used, the response of Model 4S fits the MEGATEM data north of 4200N. Note that using the proper bandwidth is critical for reproducing the early-time response. If a higher bandwidth is used (eg. 17 kHz), the response of the model is higher than the data at the first channel, but too low at subsequent early-tme channels. A bandwidth of 4 kHz fits the early-time response, and is also consistent with the waveform file.

Between 3000N and 4200N, the MEGATEM exhibits a variation in response that is not observed in the ground data: the response of the model south of 4200N is slightly too small at the early channels. This misfit increases to the south, although mid-time and late-time still fit. This is observed in the GEOTEM and VTEM data as well. To adjust the model to fit the increasing amplitude of the early channels to the south end requires adding shallow conductance. This increased conductance could be provided by several factors: a 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 drill holes 100m south. Modeling indicates the ground data are not sensitive to a thin, shallow layer at the south end of the survey with this conductance. The increased shallow 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 an arid environment causing rapid evaporation of any moisture from the shallow materials. The only remaining possibility from a geological perspective is a deeper layer of lower resistivity within the Moenkopi or at its base.

Although Model 4S fits the MEGATEM, such a 4-layer model would not have been developed by study of the MEGATEM alone. This system has limited sensitivity to the Supai Group and is unable to resolve it.

GEOTEM (Fugro Airborne)
The results for the GEOTEM are very similar to those for the MEGATEM, although the GEOTEM data is noisier than the MEGATEM. If a bandwidth of 6 kHz is used, Model 4S is a good fit to the GEOTEM data north of 4200N. 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 examined, and it was found that for a bandwidth of 6 kHz, the ground model would well represent the GEOTEM. Furthermore, this bandwidth is in agreement with the waveform file as well. Note that this is a slightly higher bandwidth than for the MEGATEM. Although both systems use the same receiver coils, there are other differences between the systems.

VTEM (Geotech Ltd)
The data in the waveform file is the derivative of the current waveform; however, we do not have information detailing how this file is collected. The current waveform utilized for modeling is a representation of the integration of the waveform file. To represent the current waveform, we utilized an exponential turn-on, the standard turn-on for ground systems, and 77% of a quarter sine for the turn-off.

When Model 4S was simulated for the VTEM system with this waveform, the response of the model was too large at late times, but too small at early times. The early-time misfit may be due to an error in the timing of the channels. If the time channels were shifted 0.03 ms closer to the end of the pulse, the difference between the model and the data was an amplitude factor of 1.15 at all but the first time channel. Thus, one possibility is that the time channels are incorrectly positioned. It was thought that this may be due to how Geotech defines the end of the pulse, but discussions with Geotech indicate that their definition is consistent with that used in the modeling software. Thus, we do not have a satisfactory resolution for this issue.

The VTEM data provided by Geotech were already reduced by dipole moment. The amplitude factor may be a result of how the data are reduced by dipole moment, or this may be one of the contributing factors. For example, the effect of multiple windings in the transmitter may not have been calibrated, or the area of the loop may not have been properly calculated. Furthermore, we do not know how the reduction is performed, i.e., whether the peak dipole moment was used for reduction, and how the peak was determined. This issue has not been resolved.

Thus, it was found that the VTEM data calibrated with the ground data if some changes to the system parameters were applied. This indicates the importance of fully understanding the system parameters for accurate modeling. Note that the data were collected in 2007 and airborne systems are continually evolving.

Conclusions

The airborne data are in agreement with the ground model except for a slight increase in shallow conductance beginning at 4200N and maximizing at the south end of the calibration site. However, some further modeling of the ground survey, in which a shallow conductive plate was inserted at the south end of the survey, indicates that the ground survey would have limited sensitivity to such a lateral variation in conductivity. Therefore, the north-south variation in response observed in the airborne data is not contradictory to the ground data results.

In our study, we have shown that airborne TEM data may be used for quantitative interpretation. Thus, it may be used to determine the host geology in mineral exploration and in other applications, including groundwater studies, as in [4].

Note, however, that for the VTEM data to calibrate with the ground data, some adjustments must be made to the system parameters. Overall, our results highlight the importance of accurately knowing the system parameters such as pulse width, exact window locations, impulse response of the receiver coils, and waveform details for effective interpretation of airborne TEM. These aspects must be accurately represented in modeling and inversion algorithms.

Based on our results, we recommend using a calibration site for airborne TEM surveys whenever the airborne data will be used quantitatively. The calibration site serves to check that the airborne data is of sufficient quality to be used quantitatively and that the system parameters are properly understood.

References

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