COMPARATIVE ANALYSIS OF AIRBORNE ELECTROMAGNETIC METHODS IN ENVIRONMENTAL, HYDROGEOLOGICAL AND GEOTECHNICAL INVESTIGATIONS

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1. Introduction

1.1 Electrical resistivity and groundwater studies

Electrical resistivity mapping has been widely used in application to various groundwater problems. Electrical properties of groundwater and aquifer rocks is a very important parameter which can directly and indirectly be used to recover structural information, geometry, porosity, depth and chemical composition of aquifer under study. Groundwater problems however require high resolution of resistivity mapping, which has been very limited until recently. With improved vertical and lateral resolution of geo-electrical methods more challenging groundwater problems can be solved in a more cost-effective way. The most cost effective resistivity mapping is provided by airborne geophysical surveys. Therefore current paper will be limited to description of such methods and their current and potential application to groundwater studies.

Electrical and magnetic properties of the rocks, which can be geophysically recovered, include dielectric permittivity, magnetic permeability and electrical resistivity. Most of the geologic information relative to groundwater applications can be recovered from recovery of electrical conductivity of the medium.

Resistivity in geophysics measured in Ohm*m and describes as the resistance of the body to the electric current flow. Electrical Conductivity (EC) is the inverse value of resistivity that measures of how well a material can accommodate the movement of an electric charge. It is a ratio of the current density to the strength of the electric field and usually measure in S/m (Siemens per meter) $\sigma=1/\rho$, however mille-Siemens per meter (mS/m) is more widely used due to the large value of Siemens (Yakubovski, Lyahov, 1988). Different rock forming minerals will
conduct EM currents differently. Two main types of conductance exist: through ionic or electronic processes. Ionic conductance is direct motion of free ions that are excited by the electric field in the medium, where electronic conductance is where the electrons restricted from free travel by strong atomic bonds, which typically happens in semiconductors. General classification of rock forming minerals includes metals, semiconductors and electrolytes. Metals, conduct electricity by moving electrons from bordering atoms which makes them most conductive and used in mineral exploration. Semiconductors use the same process, but there are much less mobile electrons making, them less conductive then metals. Solid electrolytes have transfer of electrons through the ionic substance.

Solid electrolytes make most of the rock forming minerals, where as mentioned earlier, ionic conductance happens through transfer of electrons through the ionic substances. Electrical properties of the rocks are not always controlled by the rock forming mineral, closer to the surface, in the water saturated porous media, current mostly flows through the pore-filled fluid, as the electrons are generally guided by the path of lowest electric conductivity. Salt containing pore-fluid will conduct electric current on a far greater scale then fresh water or dry rock media, therefore it is not only the mineral content of the fluid salinity, but also the effective porosity of the rock and its moisture content. This interdependence was described in 1942 by Archie’s Law, empirical relation relating formation factor to porosity of the medium in brine-saturated clean (no shale ) reservoir rocks: (1999, Mavko, Mukerji, Dvorkin ).

\[
\rho = a \rho_w \phi^{-m}
\]

\(\rho\) = bulk resistivity
a = saturation coefficient
ρw = porewater resistivity
φ = porosity
m = cementation factor

Water has a significant ability to act as a solvent. Passing through a soil column, water will dissolve many salts and elements adsorbed to soil particles. The amount of minerals dissolved in water is referred as Total Dissolved Solids (TDS) and measured in mg/L. The higher the TDS the more contaminated the water is. There is a practical relation between TDS and apparent conductivity data obtained with airborne electromagnetic survey. Pure water will still have EC, but the more dissolved ions are in the water (TDS), the higher the apparent conductivity is. Apparent conductivity is directly proportional to TDS and there is a linear relationship between those two. (Figure 1)

Airborne surveys can be quite effective in measuring apparent conductivity, further quantified by comparing remote electromagnetic conductivity data with the monitoring well data at the known depth and location. Measuring conductivity in the field is a simple process, and many instruments will provide instant readings that can be used for further correlation with the inversion electromagnetic results. The change in the slope of the derived linear relationship can also be used to estimate porosity of the aquifer, where rock with higher porosities will have higher slope of the TDS-conductivity relationship. (2005, Rubin, Hubbard)
Figure 1. The relationship of airborne electromagnetic inversion results to water quality data. (a) Peak AEM formation conductivity within the saturated zone plotted against pore water conductivity. (b) Relationship between pore water conductivity and TDS concentrations for the. (Lipinski, 2007)
Airborne Electromagnetic (EM) methods were traditionally developed for mineral explorations, but are currently playing increasing role in various environmental, geotechnical and hydrogeological applications. With increasing development of computers and computational algorithms the entire geophysical sector became a frontier for remarkable innovations targeted to significantly increase the accuracy and resolution of data, required by groundwater applications. Therefore by gradual increase in signal/noise ratio EM geophysics becomes more and more valuable for solving newer groundwater problems.

### 1.2 Basics of electromagnetic soundings theory

EM studies can be done in a number of ways and include tremendously diverse variety of system configurations and measurement techniques. In current paper we will only limit our discussion to those methods carried out using helicopter towing an electromagnetic gondola. Such methods are subdivided into two general groups: frequency domain surveys and time domain surveys, both based on the phenomenon of Electromagnetic Induction. The main goal of these methods is to obtain “sounding effect”, which is to record data, that contains geologic information from different depths and to convert these data in units of electrical conductivity/resistivity. The difference between the two approaches is that in case of frequency domain surveys the sounding effect is achieved by transmitting harmonic EM fields of different frequency and recording the secondary field using receiver coils tuned to the same frequencies as the transmitters, with lower frequencies corresponding to the deeper part of the cross-section; while time domain methods record EM signal at certain time windows (time gates), with later signal arrival times corresponding to deeper soundings.
The main idea behind both methods is based on measuring the ground response to propagating electromagnetic fields. Primary electromagnetic field is generated by passing the harmonic electric current through a transmitter coil of a circular shape. Thus the primary EM field is translated into the air and subsurface. If subsurface is homogenous, there will not be any difference in the primary EM field; however the magnetic component of the EM field will induce “Eddie” currents in conductive bodies, according to the Faraday’s Law of electromagnetic induction. Closed loop “Eddie” currents will create secondary magnetic field, which will be out of phase to the primary EM field translated by the transmitter. As a result, in any point of the space, the sum of both primary EM field generated by transmitter and secondary EM field generated by Eddie currents will induce electric field in the receiver coil.

Figure 2. Generalized scheme of the electromagnetic induction method (Reynolds 1997)
Both fields will differ in their properties such as orientation, phase, amplitude and intensity and can be further interpreted to analyze the properties of subsurface conductors. The main advantage of airborne electromagnetic methods over traditional geophysical methods is that the acquisition can be done without the physical contact with the ground. Most airborne EM systems use an active transmitter to control the properties of the signal such as wave frequency and waveform (source signal geometry), opposed to many traditional passive methods measuring natural magnetic, electrical or mechanical parameters of the subsurface. Frequency of the signal is of the great importance as the depth of the penetration is reverse proportional to the frequency of the transmitted signal, or so called ‘skin-effect’. The depth of signal penetration in frequency domain can be estimated by means of so-called skin-depth and for half-space can be estimated as:

\[
D = \frac{503.8}{\sqrt{\sigma f}} \quad \text{(Spies, 1989)},
\]

where

\[D = \text{the depth of EM field penetration (m)}\]
\[\sigma = \text{The ground conductivity (S/m)}\]
\[f = \text{The frequency of the EM field (Hz)}\]

Skin depth is such depth, where original primary magnetic field attenuates by the order of \(e\) (2.71828183 times).
In time domain similar relationship exists, however it can be written as:

\[(2) \]

\[ D = \sqrt{\frac{2t}{\sigma_0}} \quad \text{(Spies, 1989), where} \]

\[ D = \text{Diffusion Depth (Analog of skin-depth in Frequency domain)} \]

\[ t = \text{The time in seconds, after the primary EM field source has been switched off} \]

\[ \sigma_0 = \text{The ground conductivity (S/m)} \]

\[ \mu_0 = \text{Magnetic permeability of freespace (for propagation in magnetic medium this value is replaced by appropriate magnetic permeability coefficient)} \]

From equations (1) and (2) we can derive the frequency/time dependence on the depth of sounding and estimate the depth of the survey. As the EM fields propagate away from the transmitter, attenuate in the subsurface, and their amplitude decrease exponentially with depth, it becomes comparable with the level of noise in the system, so the maximum operational depth is actually not the skin (or diffusion) depth, but rather the level, at which the signal attenuates to the same order as the noise. Therefore the greater is the signal/noise ratio, the better is the resolution of the system and the better is its sensitivity to geo-electric parameters variation. This co-dependence is shown in figure 4.
2. System configurations and case studies

2.1. Systems configurations and problem description

For most environmental and hydrogeological applications the depth of the survey is not as important as the near surface resolution; however some studies require deeper penetration, such as search for deeper artesian aquifers or mapping salt/fresh water contact. The AEM systems described further operate simultaneously on several frequencies to acquire electrical properties of the apparent conductivity at different depths.
Airborne resistivity surveys can find numerous applications in environmental investigations. Electrical resistivity in the subsurface can be influenced by a number of natural or man-made factors. Landfills, chemical disposal sites, cropland salinization can alter hydrogeological parameters and be studied to determine lateral extent and penetration depth of the contaminants.

Figure 4. Example conceptual model of how EM geophysical measurements could be used at multiple scales to characterize a watershed (Robinson et. al, 2008)
Two case studies will be further described: frequency domain case study and time-domain case study. Each of the described systems is considered to be the most effective for their class, so the quality of data analyzed for these studies is the best possible. The frequency domain case study was carried out in West Virginia over 14 Coal slurry impounding structures in order to assess the safety of these structures by monitoring the hydrologic setting and to further analyze the potential for impoundments failure using the Fugro Airborne “Resolve” 6 frequency system.

The time domain study was carried out using Geotech, Ltd VTEM system in order to monitor the salinity of an aquifer in Okavango Delta region in Botswana. Another goal of the study was to modify and test the VTEM system low noise characteristics for layered-earth inversion modeling, typically used in water resource acquisitions.

2.2. Geotechnical monitoring of hazardous waste sites using Frequency Domain Airborne Systems

On February 26, 1972, a coal waste impounding structure on Buffalo Creek in West Virginia catastrophically collapsed, releasing approximately 132 million gallons of water (Davies and others, 1972). Many people were killed, injured or lost their property. This is only one of the many cases where mine impoundment failures caused tremendous damages. Currently there are strict regulations in impoundment designs, however there are still occasional breakthroughs of the water from the impoundments into the underground mines, releasing stagnant mine waters with coal slurries into the adjacent streams. To prevent further environmental damages from such disasters, federally funded study was conducted in the State of West Virginia employing Fugro Airborne Services to perform helicopter electromagnetic surveys of 14 coal waste
impoundments. The study was presumed to map the water saturated zones within the impoundments and to indentify flooded mines to reduce the chances of the coal slurry releases from such accidents.

The data acquisition was performed using RESOLVE frequency domain system by Fugro Airborne, that was attached as a sling load behind a helicopter. The system consists of five coplanar transmitter and receiver coils, and one coaxial transmitter/receiver. Coaxial coil uses frequency 3.33kHz, where coplanar frequencies are 391 Hz, 1.8 kHz, 8.18 KHz, 39.1 kHz, 132.6 kHz. System also uses a power line monitor to indentify power line noises on the 50 or 60 Hz frequency, to further exclude the evaluations of contaminated data from the final processing.

The RESOLVE system was chosen due to its sensitivity to subtle resistivity contrasts in the top 50m. The actual depth of penetration however, will also be dependant of the surrounding geology, conductivity of soil and rock and the water saturation and salinity content.

Flight lines were approximately 50m apart to obtain higher resolution, and the sensor was flown about 35m from the ground surface. RESOLVE system performs 10Hz data acquisition, meaning that at the nominal speed of 90 km/h system makes one reading every 2.5 m. Also to obtain field magnetic data, the sensor was coupled with the optically pumped cesium magnetometer that is further used for Total Magnetic Field map creation.
Figure 5. FUGRO Airborne RESOLVE system at work. (Photo by Ackman, T., 2003)
The goal of the study was to determine the zones of potential failure by using EM survey to look at hydrologic conditions within the body of the impoundment, based on the variations of the conductivity of saturating waters. The contrast in electric conductivity arises between: 1. Coal waste and bedrock, 2. unsaturated and seepage-saturated coarse coal waste, 3. consolidated and unconsolidated fine coal waste, and 4. flooded underground mines and bedrock. (Kaminski et al., 2008).

Following the survey, acquired data was processed to construct Conductivity/Depth Images (CDI) for every line flown during the survey. CDI profiles show conductivity variations from 0 to 200 mS/m and colored according to the conductivity. Standard color scheme is used for the profiles ranging from resistive (blue) to conductive (red), which allows us to interpret top 100 m of profiles to define quick alterations in water saturation. This study was verified and calibrated with DC resistivity ground survey, however we will be focusing exclusively at the airborne EM survey data.
Figure 6. The cross-section is made along one of the flight lines and perpendicular to the pond-embankment direction. The phreatic surface of the filtrate is clearly defined as a conductive contour, following the terrain at 5 to 10 meter depth. (A) This CDI section shows the invasion of waters from decant pond into adjacent aquifers. (B) This CDI shows what we interpret to be a thick plume of unconsolidated slurry underneath the embankment. Potentially this may raise concern regarding the dam stability. (C) This CDI shows a variation in apparent conductivity, which we believe suggests a spigot point change. Spigot point creates delta-like structures with coarser material deposited closer to withdrawal location and finer - deposited further away. In case of slurry, deposited into the pool - coarser material is more conductive, so changing the spigot point from one side of the pool to another (as commonly practiced in coal industry) can create a structure which is layered in terms of electrical conductivity, similar to what is observed on the figure. (Kaminski et al, 2006)
A plume of unconsolidated slurry underneath the crest of an embankment can create a potential stability danger for the waste impoundment, especially in seismically active zones and such occurrences once detected should be monitored by repeated EM ground surveys for better safety assessment. On the figure 6 CDI profile shows the unconsolidated slurry to be found underneath the embankment. It is easily distinguished because of much higher conductivity then surrounding coal waste (shown in red).

2.3 Water Resources and Salinity Monitoring Application using time-domain VTEM

Airborne system

VTEM is a time-domain airborne electromagnetic system developed by Geotech Ltd. This system was originally designed for mining exploration purposes to detect and discriminate between sulphide subsurface conductors. Transmitter loop is 26 meter in diameter and has in-loop transmitter-receiver geometry that provides high spatial resolution. VTEM has specific waveform designed for best resolution at greater depths and shown in figure 7.
Figure 7. VTEM waveform. X axis features time in microseconds, Y axis features transmitter voltage. Pulse width is 7.4 ms, (after the end of the pulse). Base frequency (full period, including 2 on-time pulses and 2 off-time cycles) is 30 Hz (Prikhodko, 2008).

All data is measured during the off-time cycle, which consists of 24 time gates (covering the range from 0.11 ms to 7.203 ms after the pulse shutdown. TEM system geometry is shown in figure 8. The system on the figure consists of the Time-Domain Electromagnetic System (VTEM), high sensitivity cesium magnetometer, similar to one used in RESOLVE system, GPS navigation system, radar altimeter and the magnetometer data is usually coupled with the magnetic data from the ground based magnetometer base station, for further diurnal corrections to the magnetic intensity data. This low noise system allows much deeper ground penetration comparing to the most up to date existing systems, high spatial resolution and improved detection of weak subsurface anomalies.
Figure 8. VTEM system flight parameters (http://www.geotech.ca)

The VTEM system is characterized by very low noise/signal ratio, due to its low noise receiver and 30Hz base frequency.

Current VTEM water resource application was indentifying freshwater resources including freshwater-saline boundary in the Okavango Delta region, Botswana and regional mapping of an area along the Taoudeni Basin boundary in Mauritania. The spatial resolution depends on the distance between the flight lines and on the generalized footprint of the system, which is in turn dependent on flight altitude and transmitter loop diameter. In our case study the lines were 2km apart, including some 500m spaced high resolution blocks, totaling 16500 line kilometers of data.
Obtained data allowed mapping of aquifers at depth of 50 meters and more (figure 9), which drastically reduced drilling cost associated with the project for a further groundwater prospecting.

Figure 9. Multi-layer 2D laterally-constrained inversion of VTEM survey data along a geologically complex system in west Africa. The spacing between each profile is 1 km (Martinez et al, 2008, Modified by Iakovlev. L).

In this figure the red colors correspond to low electrical conductance (bedrock), while the blue colors correspond to high electrical conductance (aquifers). As it can be shown some aquifers can be mapped at the depth of up to 50 meters. (Martinez, M., 2008) In figure 10 it is show that the acquisition made possible to distinguish unconfined freshwater aquifers with the extremely low salinity of almost 0 mg/l to deeper brackish aquifers with salinity reaching 5 g/l and even more. This shift happens at shallow depths of up to tens of meters and of vital interest in salinity intrusion research in the Okavango Delta area. Freshwater studies in the area are of vast
importance due to the arid nature of the region, and the follow up research should take the possibility of saline water intrusion in consideration due to the further risk of an aquifer salinization as a result of potential extensive groundwater exploitation.

Figure 10. 2D- results along a VTEM survey line across an inland deltaic environment show the freshwater-saline interface. A close-up view of the profile highlighted in the overhead photo illustrates the near-surface lateral resolution (Martinez et Al, 2008).

In this figure again red colors represent low electrical conductivity (high resistivity) and blue color represents high conductivity (low resistivity).
3. Discussion

In current study we are comparing two types of surveys in terms of their usefulness and potential application for groundwater study. It is further suggested to separate geophysical groundwater studies into different groups and to identify which parameters are critical for each study:

1. Mapping of contamination plumes and Acid Mine Drainage (AMD)

For this type of mapping it is important to keep at mind the Total Dissolve Solids (TDS) relationship to groundwater apparent conductivity. As the maximum amount of TDS in recorded in the most contaminated groundwater plumes, it is important to differentiate between even insignificant variations in groundwater conductivity, as they may be critical in terms of evaluating the TDS and the maximum allowed concentration of a particular substance. Therefore systems with high level of sensitivity and near surface resolution are preferable for such studies and out of two systems previously described the Resolve system would provide better solution.

2. Mapping of watersheds and groundwater table

Some watersheds, especially in situation with perched water table conditions may be rather thin (a few meters) and therefore for such studies a high near surface resolution is again preferred over greater penetration depth, therefore Resolve system is again the preferred tool in such groundwater application.
3. Mapping of saltwater intrusions and saltwater/freshwater contacts

Sometimes saltwater intrusions and saltwater-freshwater contacts can be followed to a significant depth and show complex geometries due to lithological variations, especially in deltaic and distributory lobe systems, furthermore it may be important to monitor such contacts to depths of several dozens of meters. Therefore in terms of selection of airborne system for this type of operations, the VTEM system is the preferred tool.

4. Mapping of geotechnical hazards

Mapping of geotechnical hazards can be done both: at depth and nearsurface. Frequency domain systems can be used here as well as time domain systems, so depending on the general task it should be decided what type of geotechnical problem has to be solved and the selection of system is absolutely dependent on the latter. For the given case study Resolve system was capable of recovering information about unconsolidated slurry body at depth of approximately 25 – 30 meters, however should this plume have occurred at depth of 50 meters it would still be a hazard for slope stability, because we would have been dealing with greater mass of embankment material topping this plume, however it would have not been recovered by such survey, while VTEM system has a record of detecting similar targets at depths up to 50-60 meters.

5. Mapping of deep artesian aquifers

In many countries such as Australia and South Africa, even in states like California and Arizona finding freshwater artesian aquifers can be a crucial component of success, however such aquifers although show enough saline material to significantly differentiate from bedrock still can be situated so deep that high resolution frequency domain methods would
not be able to detect this conductivity contrast, therefore VTEM, which has proven to be effective for such enterprises in Africa, can be the best tool for surveying.

To generalize the above observations table 1 contains analysis of system characteristics and their advantages/disadvantages regarding the described problems

<table>
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<th>VTEM</th>
<th>RESOLVE</th>
<th>Comments</th>
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</thead>
<tbody>
<tr>
<td>Spatial resolution</td>
<td>50 m</td>
<td>50 m</td>
<td>Footprint</td>
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<tr>
<td>Vertical resolution</td>
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<td>excellent</td>
<td>Top 20 meters</td>
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<tr>
<td>nearsurface</td>
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<tr>
<td>Vertical resolution at</td>
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<td>none</td>
<td>Deeper than 50 meters</td>
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<tr>
<td>depth</td>
<td></td>
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<tr>
<td>Penetration depth</td>
<td>Up to 200 m</td>
<td>50-100 m</td>
<td>Depends on the conductivity of cross section</td>
</tr>
<tr>
<td>Mapping of contamination plumes and AMD</td>
<td>To a very limited degree</td>
<td>Yes</td>
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<tr>
<td>Mapping of saltwater intrusions and saltwater-freshwater contact</td>
<td>Yes</td>
<td>Yes to a limited degree</td>
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<tr>
<td>Mapping of Watersheds and Groundwater Table</td>
<td>Very limited</td>
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### Table 1. Comparative analysis of system characteristics.

<table>
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<th>Yes to a limited degree</th>
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<tr>
<td>Mapping of deep artesian aquifers</td>
<td>Yes</td>
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4. **Conclusion**

Airborne electromagnetic geophysical surveys have been shown to be effective not only in mineral exploration, but also in various environmental applications. In the conclusion several observations can be summarized regarding the comparative analysis of the airborne geophysical systems. Both of the reviewed systems are the most advanced for their types worldwide and feature the best possible quality of airborne EM data, which was the reason for selecting them for comparison. They both prove to be effective for solving groundwater problems of different kind and with improved signal to noise ratio and stronger dipole moments of the transmitters the variety of groundwater problems can be greatly expanded. The following is the list of potential improvements in terms of system sensitivity and penetration depth:

- Improved system sensitivity would allow to differentiate between smaller variations of electrical conductivity, allowing more accurate quantitative analysis and more accurate groundwater mapping.
• Improved signal to noise ratio would allow recovering information from deeper parts of the cross-section, without losing the resolution.

• Greater dipole moment would result in stronger primary field and therefore increased depth of penetration

• Using higher sounding frequencies would provide better nearsurface resolution

• Corroborating airborne EM soundings with Total Magnetic Field measurements can be helpful when dealing with groundwater contaminated with magnetite (as in cases of mine tailings structures, or coal waste impoundments)

Finally the author would like to thank Geotech, Ltd for providing the case study and the necessary technical information about VTEM system, and further to thank fellow employees of Geotech, Ltd, Alexander Prikhodko, Eugene Druker ad Vlad Kaminski for personal consultations regarding the comparative analysis.
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