The use of airborne electromagnetic for efficient mapping of salt water intrusion and outflow to the sea

Esben Auken[1], Casper Kirkegaard[1], Joana Ribeiro[1,3], Nikolaj Foged[1] and Arjen Kok [2]

[1] Department of Earth Sciences, Aarhus University, Denmark
[2] Vitens, The Netherlands
[3] University of Lisbon, Portugal

ABSTRACT

Airborne electromagnetic (AEM) is an efficient tool for mapping groundwater resources in sedimentary environments. AEM delivers a very high data coverage and results in high- resolution electrical images of the subsurface. In particular the time domain methods (TEM) are well suited for mapping of not only the salt-fresh water boundary in the coastal zone, but also the mixing zone of fresh-salt water on the seaside. Even freshwater layers under several metres of salt or brackish water can be mapped.

Sufficient depth of investigation is obtained by time domain methods as they have a significant higher transmitter moment than frequency domain methods (FEM).

We discuss the advantages of using airborne systems in costal area for understanding of saltwater intrusion problems. Examples are shown from surveys at the vest coast of Holland and in Denmark.

INTRODUCTION

AEM is used worldwide in hydrogeophysical investigations. In particular the time domain methods offer advantages in terms of large depth of investigation, accurate mapping of a fresh-salt water boundary and a high cost efficiency. For an in-depth review of AEM methods, we refer to Fountain, 1998 while Siemon *et al.*, 2009 discuss AEM methods for hydrogeophysical investigation in particular.

We use the SkyTEM system (Sørensen and Auken, 2004), a high-resolution and high powered AEM system, and show results from two different surveys where the system have been used to map not only the fresh-salt water boundary, but also fresh water resources under a large fjord area. The examples are from the island of Terschelling (Holland) and from the Ringkobing Fjord (Denmark).

METHODS

In the following we will in general terms discuss the physics behind the TEM methods and then we give a more in-depth description of the helicopterborne TEM system, SkyTEM. Other helicopter systems like VTEM (Geotec Inc.) work similar to SkyTEM, but in our view SkyTEM offers some advantages in terms of data accuracy.

Time domain electromagnetic

Time domain AEM systems carry the transmitter loop as a sling load beneath the helicopter. In the transmitter, a current is abruptly terminated. This causes a change of the magnetic field upheld by the current which in turn causes currents to flow in the ground. Due to ohmic loss, the currents diffuse downwards and outwards in the subsurface. The change over time of the secondary magnetic fields from these currents is picked up by an induction coil, typically located near the transmitter frame. The vertical field (z-component) is measured in the receiver coil.

The rate of decay of the currents in the ground is proportional to the conductivity (or the resistivity, the reciprocal of the conductivity) of the ground. Thus by interpretation of the decay curves an accurate estimation of the resistivity structure with depth is obtained. The relationship between the rate of decay and the ground resistivity is not linear so the problem has to be solved using linearized inversion.

TEM is particularly sensitivity to low-resistive layers underlying more resistive layers. Because the formation resistivity is influenced either by the clay content or, in clay-free formations, by the ion content in the pore water, the method is well suited for mapping a saltwater boundary which can often be located with an accuracy of a few metres. A diffusive boundary will most likely be mapped as a sharp boundary.

The SkyTEM helicopter system and data interpretation

The SkyTEM system is specifically designed for hydrogeophysical and environmental investigations. During operation, the system continuously records raw data soundings, laser altitude readings, GPS positions and instrument pitch and roll for further processing and inversion. The TEM soundings are acquired alternating between two transmitter magnetic moments: a low moment for resolving the near-surface structures and a high moment for resolving the deeper layers.

SkyTEM is an absolutely calibrated system. This means that data amplifications are determined and fixed before the survey; thus data are not leveled or corrected for system responses (bias). This ensures a very high degree of accuracy and reliability of the data.

Processing of data includes application of instrument calibration parameters, correction for pitch and roll of the instrument as well as filtering of the altitude readings. The details of the processing workflow are described in Auken *et al*., 2009.

In the inversion scheme the flight altitude is included as an inversion parameter with a prior value and a standard deviation. The inversion of the SkyTEM data is furthermore done using either the 1D laterally constrained inversion (LCI) (Auken *et al*., 2005) or further development of the LCI into the spatially constrained inversion (SCI) (Viezzoli *et al*., 2009). In both cases the model parameters are tied together laterally with a spatially dependent covariance. Constraining the parameters tends to enhance the resolution of resistivities and layer interfaces which are not well resolved in an independent inversion of the soundings.

Inversion of data is done using an approach based on a local 1D forward solution and the idea of constraining neighboring model parameters to each other. When model parameters are constrained between neighboring models along the flight lines, it is termed Laterally

Constrained Inversion (LCI) (Auken *et al*., 2005), and when model parameters are further constrained to the neighboring models of adjacent lines it is termed Spatially Constrained Inversion (SCI) (Viezzoli *et al*., 2008). Adding constraints to the inversion makes it possible to resolve features that would not be seen in an independent inversion – i.e. LCI and SCI can be seen as quasi- 2D and 3D schemes, improving lateral and spatial resolution, respectively. The code is able to invert for instrument altitude in both LCI and SCI mode and provides means for carefully controlling the change of this parameter during inversion iterations.

The TEM data are not only sensitive to the subsurface resistivity structures, but data are also disturbed by the presence of wires, fences and other anthropogenic installations on the ground. As a consequence, data cannot be measured over cities, but by careful processing relatively dense areas can be surveyed. This processing is partly automatic and partly manual. An in-depth description is given in Auken *et al*., 2009.

SURVEYS

Terschelling, Holland

In autumn 2009, a 400 km large survey over the island of Terschelling on the Dutch North Sea coast was flown. The survey was part of the CLWAT project (www.cliwat.eu). The aim of the survey was to delimit the fresh-salt water boundary.

The results from the survey show that the fresh-salt water boundary and thickness of it can be accurately mapped together with the clay layers which to some extent control the groundwater flow. Also the outflow of freshwater to the sea is mapped several hundred meters from the shore line, under a more than 10 m thick layer of salt North Sea water. The results are in excellent agreement with CPT's, groundbased CVES and TEM measurement and boreholes. The investigation itself is presented in another paper at this conference.

Tingkøbing Fjord, Denmark

In late summer 2009, a 500 km survey was flown over the Ringkøbing Fjord on the Danish west coast. The Ringkøbing Fjord is a lagoon system with brackish water only connected to the North Sea through a sluice. Lines over the inlet were extended about 200 m into the North Sea. The aim of the survey was to delineate the outflow of fresh water to the North Sea, a part of the HOBE project (www.hobecenter.dk).

The results show freshwater layers consistently mapped below 2 – 5 m of brackish water and 40 – 80 m of conductive sediments. Also saltwater saturated buried valleys are recognized in the images.

DISCUSSION AND CONCLUSIONS

We have discussed the use of AEM and, in particular, the SkyTEM method for mapping of not only the fresh-salt water boundary in coastal regions but also internal layering, e.g. clay layers.

AEM is an efficient tool for a full three-dimensional resolution of the subsurface. It is cost efficient, and large areas can be mapped in detail in a relatively short time.

We have illustrated the capabilities by two examples from Holland and Denmark, respectively.

REFERENCES

Auken, E., Christiansen, A. V., Jacobsen, B. H., Foged, N., and Sørensen, K. I., 2005, Piecewise 1D Laterally Constrained Inversion of resistivity data: *Geophysical Prospecting*, 53, 497-506.

Auken, E., Christiansen, A. V., Westergaard, J. A., Kirkegaard, C., Foged, N., and Viezzoli, A., 2009, An integrated processing scheme for high-resolution airborne electromagnetic surveys, the SkyTEM system: *Exploration Geophysics*, 40, 184-192.

Fountain, D., 1998, Airborne electromagnetic systems - 50 years of development: *Exploration Geophysics*, 29, 1-11.

Siemon, B., Christiansen, A. V., and Auken, E., 2009, A review of helicopter-borne electromagnetic methods for groundwater exploration: *Near Surface Geophysics*, 7, 629-646.

Sørensen, K. I. and Auken, E., 2004, SkyTEM - A new high-resolution helicopter transient electromagnetic system: *Exploration Geophysics*, 35, 191-199.

Viezzoli, A., Auken, E., and Munday, T., 2009, Spatially constrained inversion for quasi 3D modelling of airborne electromagnetic data - an application for environmental assessment in the Lower Murray Region of South Australia: *Exploration Geophysics*, 40, 173-183.

Viezzoli, A., Christiansen, A. V., Auken, E., and Sørensen, K. I., 2008, Quasi-3D modeling of airborne TEM data by Spatially Constrained Inversion: *Geophysics*, 73, F105-F113.