Effective and accurate processing and inversion of airborne electromagnetic data

Esben Auken*
Aarhus University
Aarhus, Denmark
esben.auken@geo.au.dk

Anders V. Christiansen
Aarhus University
Aarhus, Denmark
anders.vest@geo.au.dk

Kristoffer Andersen
Aarhus University
Aarhus, Denmark
kristoffer@geo.au.dk

Gianluca Fiandaca
Aarhus University
Aarhus, Denmark
Gianluca.fiandaca@geo.au.dk

**presenting author asterisked*

SUMMARY

Airborne electromagnetic (AEM) data is used throughout the world for mapping of mineral targets and groundwater resources. The development of technology and inversion algorithms has been tremendously over the last decade and results from these surveys are high-resolution images of the subsurface.

In this keynote talk, we discuss an effective inversion algorithm, which is both subjected to intense research and development as well as production. This is the well know Laterally Constrained Inversion (LCI) and Spatial Constrained Inversion algorithm. The same algorithm is also used in a voxel setup (3D model) and for sheet inversions. An integral part of these different model discretization is an accurate modelling of the system transfer function and of auxiliary parameters like flight altitude, bird pitch, etc.

Key words: Inversion, airborne electromagnetic, AEM, LCI, SCI.

INTRODUCTION

Airborne electromagnetic (AEM) has within the last decade seen a tremendous development in technology as well as application. Many AEM systems- fixed wing and helicopter borne, transient and frequency domain – were originally developed mainly for mineral exploration. Time domain systems were developed for deep targets or targets under conductive cover and frequency domain systems for more shallow targets. In many cases the desired (and maybe possible) output from surveys are anomaly maps showing the location of possible mineralized targets. These anomalies are sufficient to start a ground based exploration program involving disciplines such as geochemistry, structural geology and more ground based geophysics. In the later years the application space has expanded and there is now a big need for geotechnical and groundwater surveys (Bedrosian., et al. 2015, Christensen, et al. 2015, Gunnink and Siemon 2015, Marker, et al. 2015). The data quality and accuracy in the processing and inversion for these targets are more demanding as geological subsurface structures only shows up in the maps as relatively limited changes in subsurface resistivity (e.g. (Jørgensen, et al. 2012)). Furthermore, with the increasing demand for groundwater caused by the globally increasing population and changed precipitation patterns due to climate changes, the need for cost effective and high resolution AEM is expected to increase significantly in the future.

A suite of processing tools and inversion algorithms is necessary to map the AEM data onto models and maps of the subsurface. Focusing on groundwater and geotechnical applications the geophysical maps are not the end result but their accuracy and scale are decisive for a subsequent hydrological modelling. Data processing is important but it is often closely related to the actual system and to some degree considered proprietary which is problematic for the processing and inversion of the data.

Inversion of AEM data is still undergoing intense research and development and only recently full non-linear inversion is possible. Even today most data sets are imaged using approximative algorithms (Christensen 2002, Macnae, et al. 1998). However, there is no longer good reasons to use these approximations as one-dimensional (1D) non-linear inversion with full modelling of the AEM system characteristic is done on standard workstations for any size survey (Kirkegaard and Auken 2015). Inversion in 3D is still very computational demanding and only a few proprietary algorithms exists (Oldenburg, et al. 2013, Zhdanov, et al. 2013).

In this keynote, we will discuss different inversions strategies for large AEM data sets for layered Earth models. A prerequisite for this to work is that we understand the AEM system well enough to include the full system transfer function in the forward modelling. Other parameters, only know with some uncertainty, has to be included as variables in the inversion. A good example is the flight altitude. We have over the years developed three different layered inversion schemes, where model parameters are constrained along the flight line, Lateral Constrained Inversion (LCI) (Auken and Christiansen 2004), along and between the flight lines using triangulation, Spatial Constrained Inversion (SCI) (Viezzoli, et al. 2008), and a full 3D discretised model cube, Voxel inversion (Fiandaca, et al.). In addition, we also have an algorithm for inverting for sheets like conductive anomalies with a varying overburden.

METHOD AND RESULTS

Forward modelling

Forward modelling is the backbone of the inversion algorithm. Writing the measured response dB_{meas}/dt outlines what is necessary to describe and model the AEM system:

$$\frac{dB_{meas}}{dt} \propto \frac{dB_{step}}{dt} \star \frac{dI}{dt} \star h_{Rx} \star h_{Tx}$$

where dB_{step}/dt is the theoretical step response (Ward and Hohmann 1988) convolved by the time derivative of the transmitter current dI/dt and the receiver transfer functions h_{Rx}, respectively. The B_{step} carries the information on the ground resistivity, transmitter shape and height, and receiver height. h_{Rx} has information on bandpass filters. It is clear that accuracy of the theoretical step response is dependent on how well all these parameters are known and how stable they are during acquisition time. The different commercial AEM systems (SkyTEM, VTEM, TEMPEST, etc.) have very different information level and some of the key parameters from a forward modelling point of view are not even measured. A good example is older TEMPEST data where the bird position and pitch was estimated from the magnitude of the primary field and not measured by differential GPS. For VTEM data the actual transmitter height was not known and data could in some cases have static shifts ((Bedrosian., et al. 2015)).

Inversion

The inversion algorithm is key to finding the subsurface resistivities. Most codes use the well-known non-linear least squares algorithm (Auken, et al. 2015). The $n+1^{th}$ iterative update of the model vector $\boldsymbol{m}$ becomes

$$\boldsymbol{m}_{(n+1)} = \boldsymbol{m}_{(n)} + \left[\boldsymbol{G'}^{T}_{(n)} \boldsymbol{C'}^{-1}_{(n)} \boldsymbol{G'}_{(n)} + \lambda_{(n)} \boldsymbol{I}\right]^{-1} \cdot \left[\boldsymbol{G'}^{T}_{(n)} \boldsymbol{C'}^{-1}_{(n)} \delta \boldsymbol{d'}_{(n)}\right].$$

Here, the parameter $\lambda_{(n)}$ is the iteratively-updated damping parameter, $\boldsymbol{G'}_{(n)}$ is the Jacobian matrix of partial derivatives, $\delta\boldsymbol{d'}_{(n)}$ the data vector update, and $\boldsymbol{C'}_{(n)}$ a covariance matrix incorporating the uncertainties of both observed data, prior information and roughness constraints. For large AEM surveys, counting hundreds of thousands of transmitter/receiver pairs, the ability for the algorithm to always find the global minimum of the object function is decisive to how well tailored the algorithm is for inversion of huge datasets. The key point here is the choice of $\lambda_{(n)}$ which steers the inversion (Auken, et al. 2015). Focused and L1 norm inversion have also been implemented (Vignoli, et al. 2015).

The numerical bottleneck is calculation of the derivatives and solving for the inverse matrix when inverting large surveys in one go. As an example, the Jacobian for a 100 000 model SCI inversion with a 30 layer discretization becomes a diagonal dominant matrix with >3 million columns. This system is solved using parallel computing and iterative solvers (Kirkegaard and Auken 2015).To speed up the forward modelling when working with time domain data the derivatives can be calculated using approximative forward responses as long as the forward calculation is non-approximative (Christiansen, et al. 2015).

LCI is used mostly for data quality check and fast initial inversion. SCI is used to produce the final products but it is expected that the conceptually much simpler voxel inversion will, with time, be algorithm of choice. Figure 1 shows a voxel domain and the resulting geophysical model (Høyer, et al. 2015).

a) b)

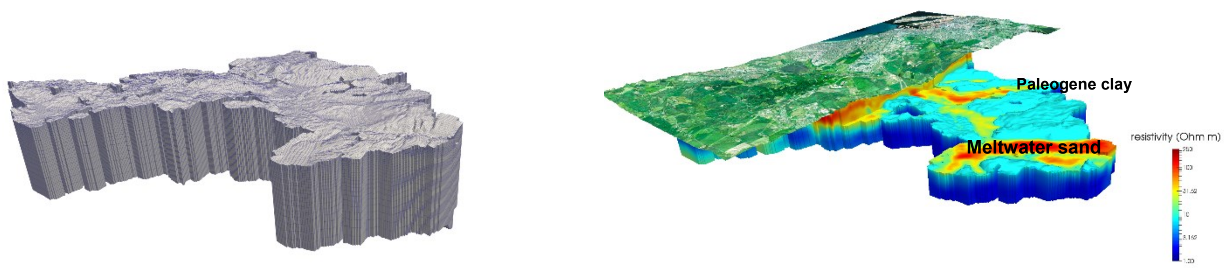

Figure 1. Voxel inversion. a) shows the voxel grid with a 30 layer vertical discretization and 40mx40m cells. b) shows a cut into the resulting resistivity model after inversion.

CONCLUSIONS

We have discussed modelling and inversion of AEM datasets and argued that full non-linear inversion of AEM frequency and time data is possible even on normal size workstations. It is necessary to accurately model the system in the forward calculation. Partly known parameters like flight altitude, bird pitch, etc. must be included in the inversion algorithm as constrained parameters.

AEM will always be a key method for mineral exploration but given new and highly accurate systems the technology combined with advanced processing and inversion algorithms is now also used intensively for geotechnical and hydrological studies.

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