Three-dimensional modeling of frequency-domain helicopter-borne electromagnetic data: A case study of the Cuxhaven Valley

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SUMMARY

Helicopter-borne electromagnetic data sets are commonly interpreted using one-dimensional modeling and inversion tools. In many cases this approach is valid (e.g., horizontal layered targets and groundwater applications) but there are areas of higher dimension that are not recovered correctly applying 1D methods. Such an area is the Cuxhaven Valley in northern Germany, which was carved by the melt-water flow after the Elster glaciation. Focused 3D modeling and inversion is required to improve the imaging of the resistivity structure of this complex geological unit. Synthetic tests using a simplified model showed that effects of 1D inversion of data from a 3D structure can be found in the vertical section across the Cuxhaven Valley assembled of 1D inversion models. On the other hand more complex synthetic models are required to explain the real data observed at the valley. The work presented here shows first systematic tests and preliminary results of 3D modeling.

Keywords: helicopter-borne electromagnetics, frequency domain, forward modeling, case study, Cuxhaven Valley

INTRODUCTION

Helicopter-borne electromagnetics (HEM) – as other airborne methods – have the advantage of fast acquisition of data with a high lateral resolution of an area due to a dense coverage. This on the other hand means that the data sets to deal with are extensive in size and handling them is time consuming. Especially modeling and inversion of such data sets using three-dimensional (3D) approaches is in most cases impractical due to computation time and memory requirements. Hence, commonly one-dimensional (1D) methods are applied, which can possibly lead to distorted models and misleading interpretations.

An example of such a higher dimensional structure is the buried Cuxhaven valley in northern Germany. HEM data was collected across this valley in the context of a survey flown in 2000. At a focused area HEM data was complemented by information from ground-based transient electromagnetics (TEM), time-domain air-borne electromagnetics (SkyTEM) and ground-based 2D resistivity sounding, and, additionally, the general structure of the buried valley was revealed by reflection seismics and drill logs (Steuer et al., 2009, and references therein).

Hence, this area was chosen for systematic 3D HEM modeling. Prior to 3D forward modeling of the valley structure systematic tests using a simplified model were conducted. Those tests allowed to identify limitations of the program/computer and helped to choose appropriate settings (e.g., lateral and vertical discretization, number and location of transmitter-receiver-positions).

HELICOPTER-BORNE ELECTROMAGNETICS

The HEM system operated by the Federal Institute for Geosciences and Natural Resources (BGR) is housed in a 10 m long tube, which is towed by a Sikorsky S-76B helicopter on parallel flight lines approximately 30 – 40 m above surface. The HEM system used in 2000 consists of five rectangular horizontal-coplanar transmitter-receiver coil pairs separated by approximately 6.7 m. The frequency range of those transmitter-receiver coil pairs covers 384 Hz to 192 kHz (Siemon et al., 2002).

The transmitter signals of the HEM system, the primary magnetic fields, induce eddy currents in the subsurface which depend on the distribution of the electrical conductivity. The relative secondary magnetic fields from these induced currents are measured in parts per million (ppm) using the receiver coils. As the penetration depth increases with decreasing frequencies the HEM system allows for different investigation depths which also depend on the conductivities present. Typical maximum investigation depths range from about 30 m in salt-water saturated sediments to about 150 m in fresh-water saturated sandy sediments or solid rocks (Siemon et al., 2012).

At each single frequency apparent resistivity and centroid depth values are derived from the data based on a homogeneous halfspace assumption (Siemon, 2001). Those sounding curves can be used to determine starting models for 1D inversion, where the in-phase and quadrature components of the measured secondary magnetic fields are mapped into resistivity models

(Sengpiel and Siemon, 2000; Siemon et al., 2009; Siemon, 2012).

CUXHAVEN VALLEY

During the quaternary glaciations subglacial melt-water erosion carved valleys in northern Europe which were filled with gravel, sand, silt and clay. Those so-called buried valleys are often completely covered by Holocene sediments and not visible in the surface morphology. One of these valleys is the Cuxhaven Valley located in northern Germany in proximity to the North Sea coast (Figure 1 & Figure 2). It is a North-South orientated valley between the cities Cuxhaven and Bremerhaven. It was formed during Pleistocene glacial regression epochs after the Elster glaciation (about 350 000 years ago) when the melt-water flow carved into Tertiary sediments (Kuster and Meyer, 1979; Wiederhold et al., 2005; Steuer et al., 2009).

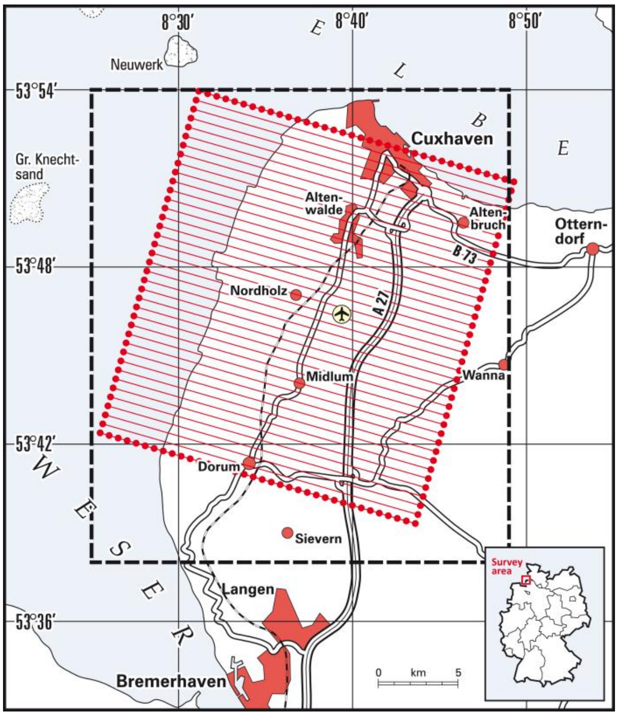

Figure 1: Location map. The red area outlines the coverage of the HEM data and the black dashed line marks approximately the area shown in Figure 2. The red square in the inlay map indicates the location of the survey area in Germany.

Figure 2 shows an apparent resistivity map based on 1.8 kHz HEM data (Siemon et al., 2001) overlain by contour lines of the Quaternary base (Kuster and Meyer, 1995). The correlation between a deep Quaternary base of the Cuxhaven Valley and a conductive nearly North-South elongated resistivity anomaly is obvious.

Steuer et al. (2009) compared the HEM data in a small selected area (close to the profile of interest; white line in Figure 2) with airborne time-domain electromagnetics (SkyTEM), ground-based transient electromagnetics (TEM) and 2D resistivity soundings. Additionally, they used information about the general structure of the Cuxhaven Valley provided by reflection seismics and drill logs. They found a continuous, conductive near-surface layer seen by HEM and 2D resistivity sounding but too shallow to be resolved by TEM and SkyTEM. This layer was interpreted as Holstein clay. Within the valley they found a second, deeper conductor (consistently seen by all EM methods) that is interpreted as Lauenburg clay.

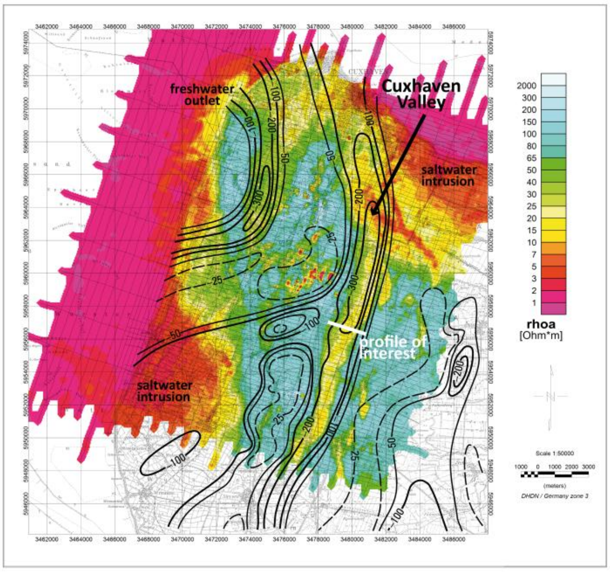

Figure 2: Apparent resistivity map derived from HEM data at a frequency of 1.8 kHz (after Siemon et al., 2001) including contour lines of the Quaternary base in meters (after Kuster and Meyer, 1995). The white line shows the location of the profile of interest.

To date the HEM, TEM and SkyTEM data are only modeled and interpreted based on 1D approaches. Figure 3 shows a vertical section of the resistivity distribution (based on 1D inversion models) recovered from HEM data along the profile of interest. The conductive anomaly in about 40 m depth is the Lauenburg clay layer inside the Cuxhaven Valley.

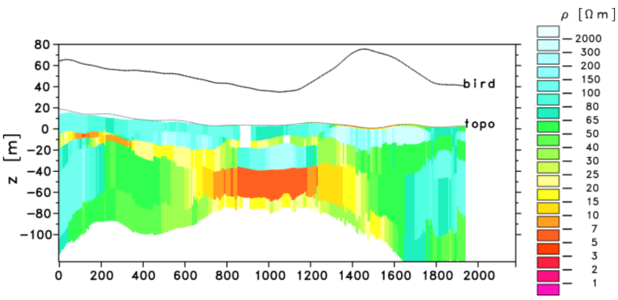

Figure 3: Vertical section assembled of 1D inversion results of real data. The location of the profile is indicated by a white line in Figure 2.

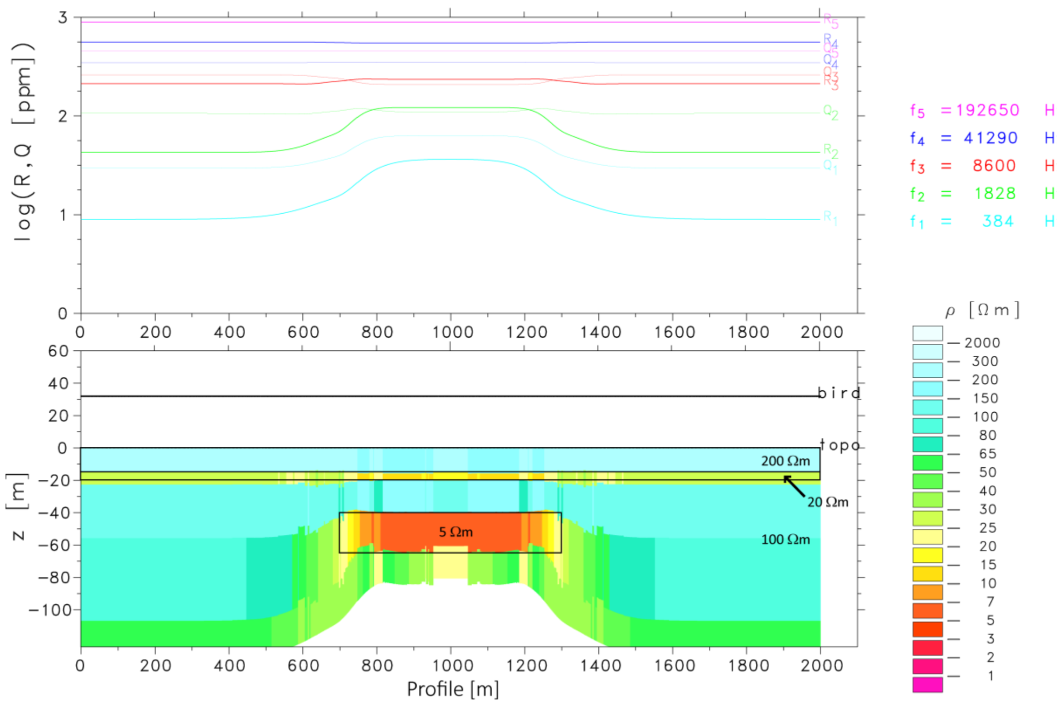

Figure 4: Synthetic data (top) and 1D inversion models (bottom) obtained from a simple model. The obtained synthetic data (in-phase R, quadrature Q) in ppm are shown for all 5 frequencies (color coded). The 1D inversion models are assembled as vertical section (see color bar for resistivity values). The black lines and resistivity labels written on top of the section describe the original model used (layered halfspace with block). The boundary to the 10 Ωm halfspace in 160 m depth is not recovered correctly but indicated by the slightly higher conductivity below 105 m.

3D MODELLING

First simple modeling tests were carried out using the code MarcoAir developed by Xiong, Raiche and Sugeng as part of the AMIRA project P223D. This integral equation code uses a system iterative method for solving the matrix equation and allows symmetric structures with two symmetry planes. The symmetrical considerations save both computation time and storage requirements (Xiong and Tripp, 1995).

On the basis of the Cuxhaven valley model, a very crude model was designed to test the modeling parameter settings. The model consists of a single conductive block (600 m x 600 m x 25 m, 5 Ωm) representing the Lauenburg clay embedded in a simple layered halfspace. According to the used BGR HEM system data were calculated for 5 horizontal-coplanar transmitter-receiver coil pair (separation 6.7 m; 384 Hz to 192 kHz). Comparison of the 3D forward responses with exact 1D forward solutions (Siemon et al., 2009, Siemon 2012) showed that discrepancies of the highest frequency (192 kHz) are related to the quasi-stationary solution applied. Discrepancies of the other frequencies are dependent on the discretization of the block, and hence, a trade-off between accuracy of the solution and computation time and memory requirements. For the simple test model a discretization of 25 m x 25 m x 5 m is considered as good choice.

Data along a profile across the center of the block were calculated using a site spacing of 2 m and a sensor height of 32 m. The resulting data set was inverted applying standard 1D tools (Siemon et al., 2009, Siemon 2012). Note, that the quasi-stationary solution was used to match the algorithm of MarcoAir rather than the exact solution. Figure 4 shows the obtained synthetic data of all 5 frequencies (top) and a vertical section merged of all resulting 1D inversion models (bottom). For comparison the original synthetic model is sketched on top of the section (black lines and written resistivity values). It is obvious that far away from the block 1D inversion models recover the structure reasonably well. The slightly more conductive layer below 105 m is an artifact of the 10 Ωm halfspace below 160 m, which has an influence on the lowest frequency. Additionally, differences between the 3D forward algorithm and the 1D forward code used within the 1D inversion program result in small discrepancies in the synthetic data, which cause the 1D inversion models not to recover the true structure accurately. In the center of the block, 1D inversion results also recover the top three layers and the block itself well, but – as already well known (Sengpiel and Siemon, 1998) – the resistivity below the conductor is underestimated. Close to the edges of the conductive block 1D inversion models clearly fail to represent the resistivity structure correctly. While the thickness of the

block first decreases and then increases towards the edge the resistivity is increasing. This leads to an image of an upwards bend conductor of changing resistivity with downwards smeared less conductive tails to each side.
Although the real data situation is more complex (i.e., varying topography, varying sensor height and a more complex background structure), a firstly upwards and then downwards bending of the conductor and an increasing resistivity as well as an underestimated resistivity beneath can also be found in the vertical section (Figure 3). It is obvious that the 1D approach is not recovering the true resistivity structure of the valley and on the other hand the presented synthetic model is too simple to represent such a complex structure. Hence, further 3D modeling and inversion is required to improve the image of the resistivity distribution.

CONCLUSION

Using airborne electromagnetic surveys huge areas can be surveyed almost completely in a relatively short time at economic cost. On the other hand those data sets are of enormous sizes and difficult to handle. Therefore, full 3D approaches for modeling and inversion are in most cases impractical with respect to the computational costs. Using a 1D approach the majority of those data can be inverted with satisfying results. But there are small areas – especially close to resistivity contrasts – where approaches of higher dimensions need to be considered to avoid distorted and misleading models and interpretations. (See Ullmann et al. 'Automatic detection and classification of induction anomalies in helicopter-borne electromagnetic data sets' in this abstract collection for a method to distinguish whether 1D is appropriate or not.) Based on the case study of the Cuxhaven Valley focused 3D modeling and inversion is applied to improve the imaging of the resistivity structure. First systematic tests and preliminary results will be shown.

ACKNOWLEDGMENTS

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