

SkyTEM Case Study:

SkyTEM¹⁰¹ – A New Airborne Mapping Tool

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ABSTRACT

Groundwater models are an essential decision tool for the administration and evaluation of groundwater resources. To establish reliable models high-resolution measurements of geological structures are required putting increasing demands on the quantity, density and quality of the data collected. The financial and physical constraints of drilling make the application of near surface airborne geophysical techniques appropriate for data collection; however, is this data sufficient to have confidence in the formulation of a reliable model?

THE SKYTEM METHOD

The SkyTEM airborne electromagnetic method (AEM) is based on the further development of ground based TEM equipment (Transient Electromagnetics). AEM is used for indirect measurement of the subsurface down to depth while at the same time providing large area coverage. In Denmark, the airborne method is used to map deep geological structures and aquifers but has been faced with the challenge of obtaining detailed resolution of the upper 10-15 metres. Recent major advances in instrumentation have led to the development of the SkyTEM¹⁰¹ system that is capable of delivering efficient and detailed mapping of near surface layers.

The SkyTEM method consists of a non-metallic frame suspended under a helicopter (Figure 1). A transmitter coil mounted on the frame creates a powerful high intensity primary current that creates (secondary) electric eddy currents in the ground. When the primary current in the coil is turned off abruptly the secondary magnetic field in the subsurface begins to decay. The decay rate of the secondary field is measured in the receiver coil fixed on the frame. The rate of decay of the secondary field is dependent on the resistivity of the ground, which can vary within subsurface geological layers. Based on this rate of decay values of the electrical resistivity of the layers can be calculated. For example, clay sediments are characterized by low resistivity, whereas layers of sand or gravel have a high electrical resistivity. More resistive ground is

characterized by a short response as the magnetic field fades more quickly.

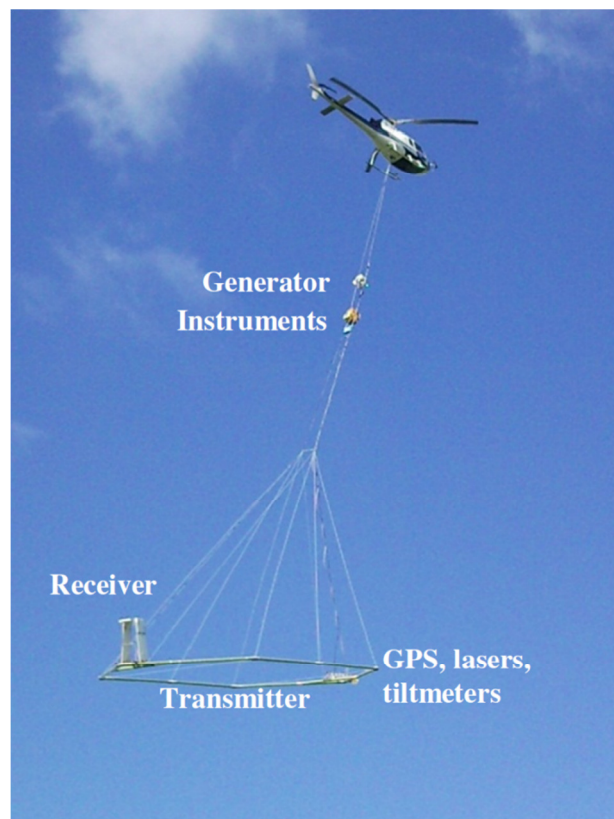


Figure 1: The SkyTEM¹⁰¹ system

SKYTEM¹⁰¹ AND DATA PROCESSING

The SkyTEM¹⁰¹ system was developed for the NiCA project (Nitrate Reduction in a Geologically Heterogeneous Catchment – www.nitrat.dk) for the purpose of modeling the presence of nitrate in near surface aquifers and nitrate that is leaching into the connected streams.

In order to model nitrate changes in the upper 30 metres of the subsurface very detailed heterogeneous descriptions of the geological structures are required. This makes further demands on the ability to achieve reliable near surface resolution. In order to collect this near surface data the SkyTEM¹⁰¹ system, characterized by a much higher surface resolution and quicker production time, has been developed along with a new data processing algorithm in the Aarhus Workbench software. The development of the SkyTEM¹⁰¹ system and Aarhus Workbench encompasses:

- 1) *A newly engineered transmitter coil frame constructed with an aerodynamic profile with an area of only 132 m².* Less air resistance and lighter weight means the system can be flown more easily at the nominal flying height of 30-40 metres and consequently, data can be collected at an average flight speed of 100-140 km/h. In comparison, conventional airborne systems with a frame size of 300-500 m² are typically flown at a speed of 50-80 km/h. The SkyTEM frame is designed to be self-adjustable in the air and remains more or less horizontal to the ground regardless of flight and wind speed.
- 2) *Advanced instrumentation to optimize the turn-off process of the transmitter coil.* The transmitter current turn-off time has been reduced to a very fast 4 μ s making it possible to record information from very early times and hence from the near-surface geology. This latest optimization of the turn-off process makes the first usable time gate measure at 5 μ s, or just 1 μ s after turn-off of current. No other helicopter-borne transient electromagnetic system is capable of achieving this early a turn –off time. This development now makes it possible to obtain a detailed description of the upper soil layers from 1-2 metres below the subsurface and up to a depth of 80-130 metres.
- 3) *A new technique for correction of the (primary) transmitter current from the response of early time data.* This correction enables the use of data after only 1 μ s from turn-off of the current and is applied as part of the data interpretation.
- 4) *A new data processing algorithm.* This algorithm in the Aarhus Workbench ensures that early time data are averaged as little as possible while still obtaining a good signal to noise ratio. A sounding for each 15

m on the ground is produced. with a flight height of above 50 m uses a larger averaging.

THE NORSMINDE MAPPING

The SkyTEM¹⁰¹ system was tested in the Norsminde Fjord catchment in Denmark as a part of the NiCA project. The purpose of the geophysical mapping was to map the near surface aquifers by producing a detailed description of the geology in the upper 30 metres. This geophysical mapping then forms the basis of detailed geological and hydrological models for determining the transport and reduction of nitrate in the catchment.

The area mapped comprises 101 km² of the catchment of Norsminde Fjord. The geology of the catchment is complex and can be divided into units consisting of glacial beds, Miocene beds, Eocene beds, buried valleys and glacial tectonic complexes.

The project was conducted by SkyTEM Surveys ApS, Aarhus Geophysics ApS and the HydroGeophysics Group, Aarhus University, in June 2010 and was divided into three phases. In Phase 1 the mapping was designed with a spacing of 100 metres between flight lines. The flight lines are marked in black lines in Figure 2. In total 1203 km were mapped in Phase 1 in 13 hours and 26 minutes. Coverage could have been achieved more quickly but the flight speed was reduced to a maximum of 100 km/h for testing purposes. In Phase 2 it was decided to fly between the Phase 1 flight lines to achieve higher data density in the western part of the mapping area and the flight line spacing was reduced to 50 metres. The flight lines in Phase 2 are marked in red lines in Figure 2. A total of 465 km of data were flown in 5 hours and 6 minutes in Phase 2. In Phase 3, 178 km were flown in two hours, and the flight lines cross the lines from Phases 1 and 2 to determine if the resolution of the geology in this area could be improved. The flight lines from Phase 3 are marked in green lines in Figure 2.

Together the 101 km² catchment was mapped in only four days, and a total of 1,846 kilometres of data were collected consisting of more than 100,000 individual soundings.

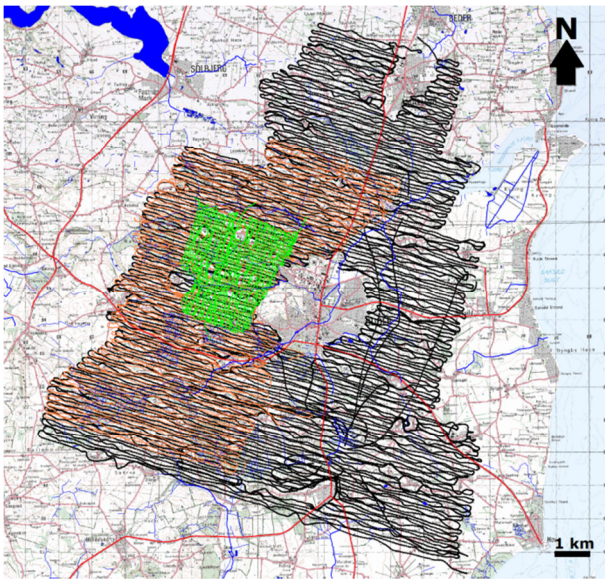


Figure 2: Flight lines from the mapping of the Norsminde catchment

RESULTS

After data collection the raw data was processed in the Aarhus Workbench to remove noise. Coupled data arising from man-made installations such as buildings, power lines, cables, roads and railroads was also removed. The average flight speed of the entire survey was approximately 100 km/h or 28 metres per second. The average flight height for the transmitter frame was 30 metres above ground level. Typically, a repetition frequency of one full measurement every half second is used, thus, with a flight speed of 28 metres per second the lateral distance between the raw data sets is approximately 14 metres. Raw data is stacked during processing to enhance the signal-to-noise relationship, and in reality the resolution is 25-50 metres horizontally and less than a few metres vertically.

After initial processing the data is interpreted using an interpretation algorithm implemented in the Aarhus Workbench yielding a quasi 3D model of the resistivity of the subsurface down to 130 metres below ground level. Subsequently the geophysical models are presented as average resistivity maps at various elevation or depth intervals (Figure 3) or in profiles (Figure 4). Figure 3 shows a middle resistance map for a depth of 15-20 metres. In general, there is a good correlation between resistivity and deposits of clay or sand. Clayey sediments typically have a resistivity of less than 50 Ω -m, whereas gravel and sand have a resistivity above 60 Ω -m. The paleogene clay in the catchment is characterized by a very low resistivity of approximately 2 Ω -m.

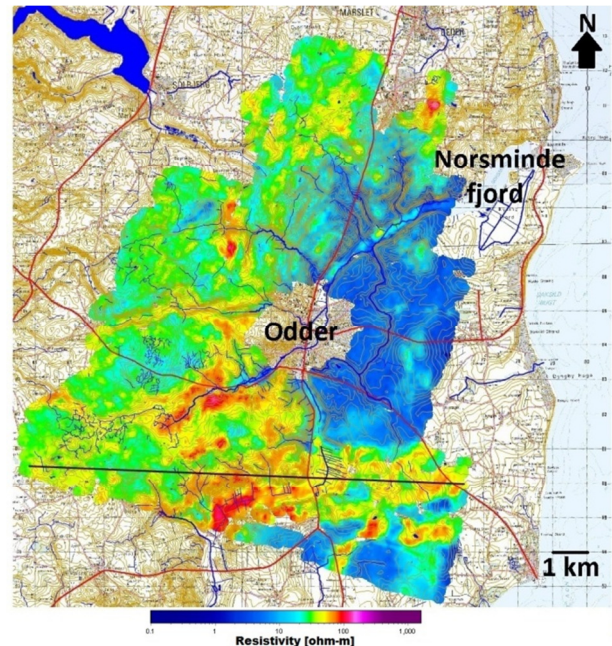


Figure 3: The mid resistivity map for a depth of 15-20 metres. The position of the profile in Figure 4 is marked in a black line. The map also shows the contours, in many places with a direct correlation with the geology.

As shown in the average resistivity map, the level of detail is very high, and large variations in local resistivity are seen and are representative of the distribution of sand and clay. Information about the three-dimensional distribution of these local deposits of clay and sand is vital in order to model the nitrate reduction in the near- surface aquifers.

COMPARISON WITH DRILLINGS

In order to examine and validate the near-surface resolution of the SkyTEM¹⁰¹ system and the data processing system, the geophysical results were compared with both new and existing data from drillings in the Norsminde area. All drillings within 15 metres from a flight line are included in the validation. A total of 54 drillings were within this interval however, data was only available for 46 drillings. All available data from these drillings was analyzed and a detailed comparison with the geophysical models was made.

The method of comparison was to plot the geophysical models in profile together with the lithological information from the drilling and then evaluate their consistency and correlation. In the comparison, the quality of drilling data was carefully assessed by reviewing drill test descriptions, well drilling reports, and drill site locations. The quality of drilling data can be affected by factors such as lack of sampling or less than adequate description of the sampling, the drilling method used and not least, incorrect coordinates.

Upon comparison of the drilling data and airborne geophysical models the results were divided into four categories of consistency: “very good correlation”, “good correlation”, “poor correlation” and “no correlation”.

In areas of “very good correlation” the criteria was that geophysical models should display low resistivities (i.e. $<50\text{-}60\ \Omega\text{-m}$) where drilling data shows clayey sediments - typically moraine clay, meltwater clay and mica clay. In areas with paleogene clay deposits resistivities are very low the resistivity measurements should be $<10\ \Omega\text{-m}$. When the drillings contain sand or gravel, high resistivities should be seen in the models (i.e. $> 50\text{-}60\ \Omega\text{-m}$). Furthermore, there must be a consistency regarding the exact positioning of layer limits and hence the thickness of the individual layers. The assessment “good correlation” typically denotes small inaccuracies in the consistency between the positioning of layer limits. Examples are an inaccuracy of 3 metres in a layer limit of 15 metres depth, or a single thin layer of 2-3 metres not resolved in the top 10 metres. The assessment “poor correlation” denotes that there is some consistency and usable data can be extracted from the SkyTEM¹⁰¹ data, whereas in case of “no correlation” no detectable correlation could be made.

Of the 46 drilling locations in the comparison, the consistency was distributed as follows:

- 43.5% “very good correlation”
- 32.6% “good correlation”
- 17.4% “poor correlation”
- 6.5% “no correlation”

Consequently, for 76% of the drillings the correlation is either very good or good, which is a promising result. This means that in only 11 drillings of 46 exhibit poor or no correlation. Subsequently, the causes of these inconsistencies were assessed, and the reasons identified were (1) bad drilling quality, (2) erroneous localization of the drilling, (3) couplings to electrical installations or data noise, (4) increased saline content in the pore water, and (5) 3D effects and limitations in the resolution of the system. The assessment proved that about one third of the cases of poor or no consistency were related to erroneous or poor drilling data (1+2), whereas two thirds of the cases are due to factors that are related to the mapping method (3+4+5). The most predominant reason (5) is 3D effects and limitations in the resolution of the system.

Most cases of poor or no correlation were located in the northern part of the area where the geology is strongly deformed by glacial tectonics. It is not surprising then that the system is unable to resolve the geology and reproduce drilling data since the heterogeneity is far below the horizontal resolution that can be expected from geophysics.

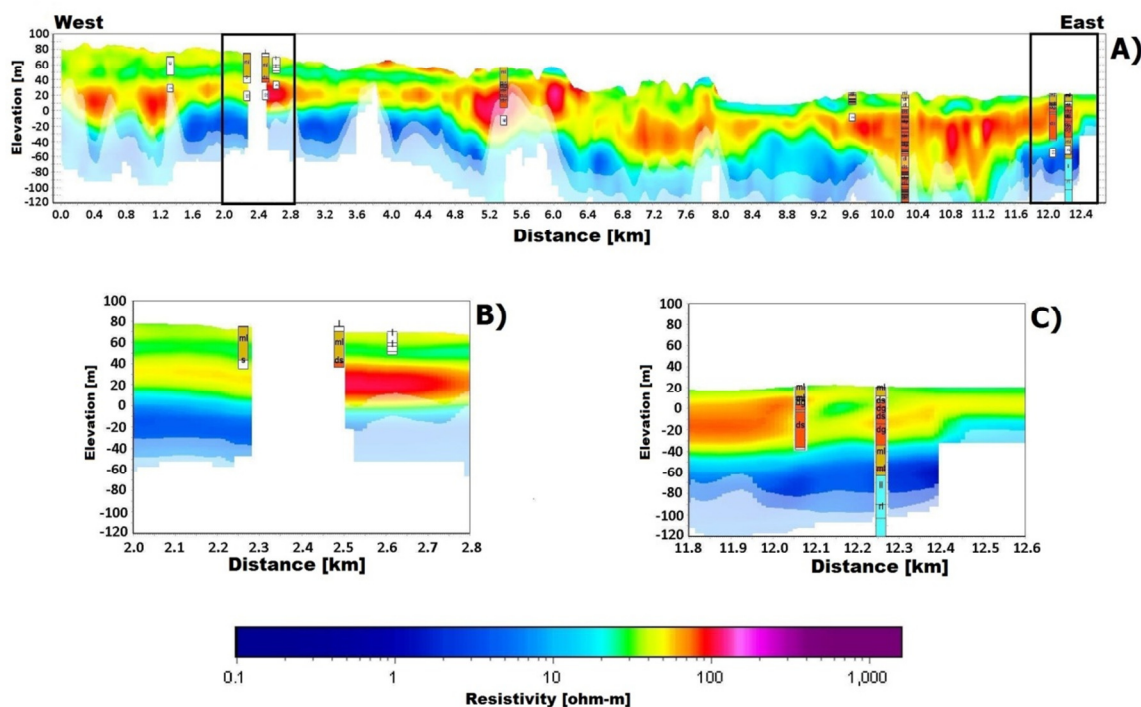


Figure 4: SkyTEM¹⁰¹ results from the Norsminde catchment. A) Geophysical profile with drillings. B) and C) Zoom of profile. Legend: s = sand, ds = meltwater sand, dg = meltwater gravel, rl = Røsnæs clay, ll = Lillebælt clay, l = clay and ml = moraine clay

Figure 4 shows a profile of the geophysical results compared with drillings in the area. The correlation is either very good or good. The position of the profile is shown in Figure 3. The profile in Figure 4A illustrates the complex geological structure in the Norsminde catchment with glacial beds, buried valleys and paleogene clay. Furthermore, it is worth noting the good correlation between resistivities and drilling information in both the top 30 metres of the subsurface as well as in the deeper soil layers. There is obvious correlation where the clayey sediments have a resistivity below 50 Ω -m, and the sandy and gravelly meltwater beds have a resistivity above 60 Ω -m. Figure 4B is an enlarged area profile with three near-surface drillings at a depth of 23-40 metres. The near-surface moraine clay is well resolved, and the depth to the meltwater sand is clearly identifiable in the geophysical models. In Figure 4C the focus is on an area in the profile with a more than 140 metres deep drilling.

PERSPECTIVES

The comparison between the SkyTEM¹⁰¹ results from the Norsminde catchment with 46 drillings demonstrate a very good or good correlation for 76% of the drillings. Only 6.5% of the drillings (three drillings) showed inconsistency. This proves that a good near-surface resolution has been achieved using this recently re-engineered airborne system.

The results from this project open up new ground for employing airborne geophysics with confidence to create detailed near-surface geological models that can be used to map ground water recharge areas or areas where the groundwater may be vulnerable to the activities of humans. Previous models of the SkyTEM system were focused on achieving increased depth of investigation to map the deep aquifers, but the newly developed SkyTEM¹⁰¹ system produces results that can also be used for a wide variety of near-surface geological mapping. In particular, the technique can be applied to geological and hydrological exploration to locate shallower secondary aquifers, salt water encroachment, wetlands, pollution plumes or a detailed vulnerability mapping in the form of clay thickness maps.

The results obtained by SkyTEM¹⁰¹ are also important and relevant for geotechnical engineering challenges such as characterization of large or inaccessible areas, road, railway, pipeline or levee construction or the detection of man-made buried metallic objects. The SkyTEM¹⁰¹ can also be applied in connection with climate change. As we anticipate longer and more intense periods of precipitation in some

areas of the world, or conversely, low to no precipitation in others, mankind will need a method to reliably and quickly characterize the top soil layers and aquifers in order to predict the need for drainage or protection of our infrastructure.

Furthermore, farmland and other open areas can play an important role in water re-charge and retention. SkyTEM¹⁰¹ data may contribute to assigning the proper designation for current and future land use and form the basis for more precise planning of crop fertilization. This will help us to meet the demand for increased crop yields at the same time as protecting our environment and helping us achieve sustainable development.