An overview of the newest SkyTEM and inversion technologies with focus on resolution of shallow geological layers

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Introduction

Airborne electromagnetic methods (AEM) have in the last decade undergone immense hardware and software developments. 10 years ago high resolution shallow surveys for geotechnical engineering, aquifer mapping, landslides etc, could only be done by frequency domain methods whereas time domain methods were more suited for deep measurements. Today, the development of the time domain methods has reached a level where the same or even better data from an airborne platform is obtained compared to the best groundbased system. Also, data inversion has changed from being dominated by approximate algorithms to full solutions modelling the complete system characteristics with inversion of thousands of line kilometers of data in one run. These inversions are possible because the algorithms use multithreaded architecture, which efficiently runs on small workstations or severs.

In this paper we discuss the newest hardware developments of the SkyTEM system and also how these developments are accompanied by inversion algorithms closely adapted to the hardware. The SkyTEM system, as shown in Figure 1, originally developed at Aarhus University, is now operated and developed by an independent spin-off company, SkyTEM Surveys, while inversion and processing algorithms are developed at Aarhus University. However, there are fruitful collaborations and SkyTEM Surveys identify themselves as a high-tech company with an ambitious research and development (R/D) program.

System hardware

High resolution surveys with targets within the depth range of 0 to 100 m puts very high demands on the hardware and the engineering of the transmitter and receiver framework. To obtain resolution right from the ground surface the key point is to measure very early times in the order of micro-seconds from the turn-off of the current in the transmitter frame and sample the signal very dense in both time and space. SkyTEM is characterized by a few unique designs making it possible to push the technology to its physical limits.

The first important design is the location of the receiver coil where the summation of the primary magnetic field from the octal-shaped transmitter frame is zero or very close to zero (Sørensen and Auken 2004). This design avoids troublesome bucking coils to compensate the strong primary field and, as important, the fields from small exponential decaying currents still present in the transmitter coil in the first microseconds after the turn-off are also minimized. The zero position of the coil is a well-known technique, but to obtain very early times other techniques are neeed as well. Hence, in the later years there has been developed several field compensation schemes in order to obtain times gates from 0 – 10 μsek. The first scheme was named Coil Response Compensation (CR) and was based on measurements of the primary field in a high altitude followed by an inversion for the earth model parameters including an extra scale factor parameter scaling the amplitude of the primary field (Schamper, Auken and Sørensen 2014). The second scheme called Primary Field Compensation (PFC) is also based on a scaling of the primary field measured in high altitude but it is combined with a measurement of the coupling between the transmitter and the receiver. It also uses a special linear ramp-in transmitter waveform. The PFC is applied at each individual transient and is much more accurate than the CR compensation. The PFC has in the third scheme been further developed so the full impulse response of the system can be measured and given as input to the forward modelling algorithm. The benefits of this scheme are immense as the impulse response includes the transmitter waveform, receiver coil and effects of the receiver electronics. The scheme has not been put into routine production yet, but it opens for the possibility to even invert on the data measured during turn-off, hence gates can be used from time 0.

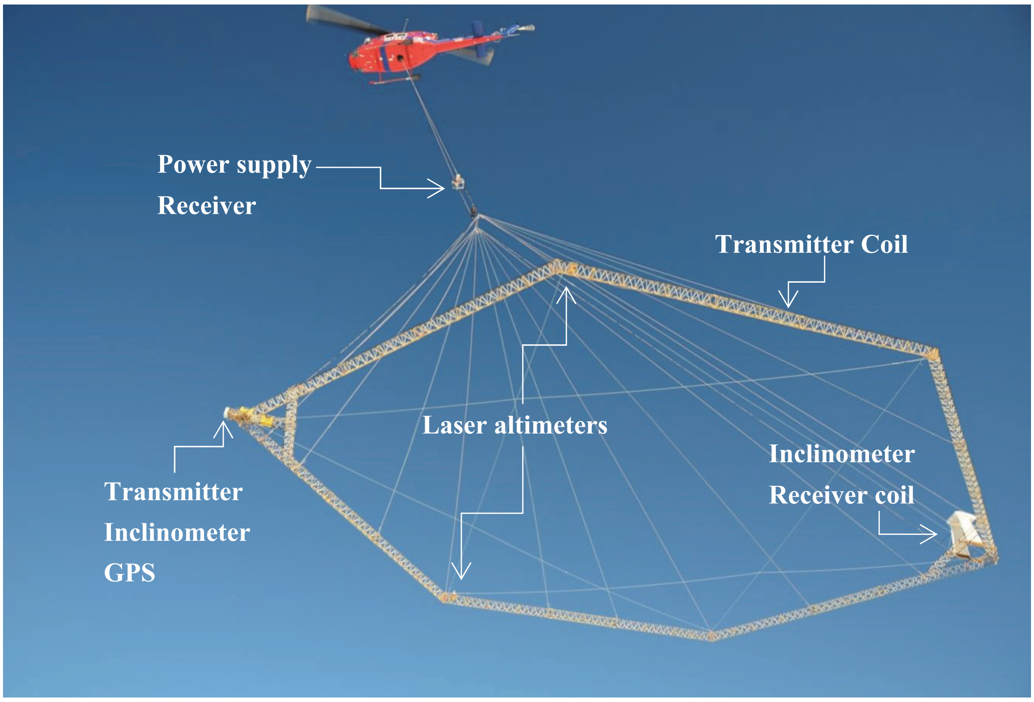

Figure 1: *The SkyTEM system with indications of the most important devices. The framefafa on the picture is outdated as the system is now operated with a composite material frame with a smaller air resistance and better stability, but the overall layout is the same.*

The second important design is the ability to apply different transmitter moments; early times are measured with a low moment while late times are measured with a high moment. This scheme has always been one of the characteristics of the SkyTEM system and was actually inspired by the old analog Protem 47 instrument, which used different repetition frequencies to measure different time ranges. The back side of the scheme is that the system moves a number of meters on the ground while a moment is being transmitted leaving smaller lateral "holes" in the data. This is not problematic when flying 10 – 20 m/s but flying 30 – 50 m/s it becomes problematic to obtain sufficient continuous sampling of the surface. A recent reprogramming of the transmitter system has made it possible to transmit one or more small pulses at the end of the large pulse thus obtaining continuously sampled data. The waveform need to be modelled in the forward calculation for this to work.

The PFC scheme with measurement of the system impulse response can only be done with an airborne system as it is dependent on measurement of the impulse response at high altitude where the response from the Earth is absent. The fact that times during the turn-off or at least times right after, can be used makes us believe that data from the airborne system when it comes to resolution of shallow geological layers is at least as good as from any groundbased TEM system, if not better.

Forward modelling and inversion

The SkyTEM system R/D is closely integrated with developments in the inversion kernel AarhusInv (Auken et al. 2014). AarhusInv is also the inversion engine in the software used for processing and presentation of AEM data, Aarhus Workbench (Auken et al. 2009)

AarhusInv has in the later years undergone major design changes and it now uses sparse storage of all matrixes and it implements sparse solvers and matrix-vector-matrix products. OpenMP is implemented nested and results in an almost linear speed up from 1 to 64 CPU´s (Kirkegaard and Auken 2014). The implementation makes it possible to run laterally or spatially constrained inversions (Viezzoli et al. 2008) on 5000 – 10000 km of data in one run avoiding dividing data in smaller parts and avoiding any overhead related to such subdivisions.

A recent major development has been the voxel inversion (Fiandaca et al. 2014) which we believe will be the favorite inversion method in the future. The voxel inversion operates with a model description in a 3D unstructured grid but with 1D forward responses and derivatives. It efficiently decouples the data space from the model space, hence the model discretization becomes independent of the data sampling. Parameters like flight altitude, which normally need to be part of the inversion, is handled separate, as they cannot be decoupled from the data location. The scheme opens up for a simple implementation of joint inversion of AEM and groundbased data and a-priori inversion is easily added to voxel nodes.

The forward modelling of AarhusInv includes implicit description of the different parameters of the system. This is the current waveform described piece wise linear, the bandwidth characteristic of the receiver coil and the receiver and an open/close gate in the receiver coil. As an alternative to model the individual parts of the system response, the total system response, the impulse response, can convolved with the step response. This opens for using very early times and research is currently done to verify the credibility of the gates measured during the turn-off of the current.

Conclusions

The SkyTEM technology is being intensively developed to measure earlier times. The hardware developments has opened a new suite of applications where high resolution surveys can be carried out for e.g. geotechnical applications, landslide mapping ect. The developments in hardware is accompanied by developments in inversion software which fully utilize the data. The newest developments includes PFC and here data are expected to be useable also during the actual turn-off of the ramp while the full impulse response of the system is measured and used during data inversion. 3D voxel inversion fully decouples the measurement location form the model space and is expected to be the preferred inversion method in the future.

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