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SkyTEM – a new high-resolution helicopter transient electromagnetic system

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Key Words: electromagnetic methods, airborne electromagnetic, transient electromagnetic, time-domain electromagnetic, helicopter electromagnetic, HTEM, SkyTEM, hydrogeology, hydrogeological investigation

ABSTRACT

SkyTEM is a time-domain, helicopter electromagnetic system designed for hydrogeophysical and environmental investigation. Developed as a rapid alternative to ground-based, transient electromagnetic measurements, the resolution capabilities are comparable to that of a conventional 40×40 m^2 system. Independent of the helicopter, the entire system is carried as an external sling load. In the present system, the transmitter, mounted on a lightweight wooden lattice frame, is a four-turn 12.5×12.5 m^2 square loop, divided into segments for transmitting a low moment in one turn and a high moment in all four turns. The low moment uses about 30 A with a turn-off time of about 4 µs; the high moment draws approximately 50 A, and has a turn-off time of about 80 µs. The shielded, overdamped, multi-turn receiver loop is rigidly mounted on the side of the transmitter loop. This is essentially a central-loop configuration with a 1.5 m vertical offset.

In vertical hover mode the SkyTEM responses were within 2% of those from a conventional ground-based system. Instrument bias level is not a concern as high-altitude tests showed that the background noise level is higher than the instrument bias level. By inverting a sounding from a test site to a standard model and then applying the SkyTEM system parameters to compute the forward response, conventional measurements were within 5% of SkyTEM responses for flight heights of 7.25, 10, and 20 m. Standard field operations include establishment of a repeat base station in the survey area where data are acquired approximately every 1.5 hours, when the helicopter is refuelled, to monitor system stability. Data acquired in a production survey were successful in detecting and delineating a buried-valley structure important in hydrogeophysical investigations.

INTRODUCTION

Airborne electromagnetic (AEM) systems have been in use for over 50 years (Fountain, 1998). The first attempts in the 1950s were quite successful in base-metal exploration in Canada, and in that decade over 10 systems were in the air (Palacky, 1986; Palacky and West, 1991). The most successful system to come out of the 1950s was the Induced PUlse Transient (INPUT), accounting for roughly 70% of contract airborne surveys (Barringer, 1962). A two-frequency quadrature system was developed in Finland and the first survey covering an entire country was flown in 1972 (Peltoniemi, 1986). Canada and the Nordic countries led in the development and use of AEM systems, but by the 1970s the methodology was seeing worldwide use. With the decline in exploration for base metals, the use of AEM methods turned from anomaly detection to conductivity mapping and frequency-domain helicopter EM (HEM) systems began appearing (Fraser, 1978). By the 1990s base-metal exploration was concerned with deep targets, and AEM systems began to follow two paths: fixed-wing time-domain systems designed for detection of deep conductive targets, and frequency-domain HEM systems intended for high-resolution, near-surface, conductivity mapping.

Of the more than 30 systems that have made their appearance since the inception of the AEM method, only a few are currently in routine use. The GEOTEM system (Annan, 1990; Annan et al., 1996), and the larger moment MEGATEM (Smith et al., 2003), are digital enhancements of the INPUT system, which uses a half-sine transmitter waveform. The TEMPEST system uses a square transmitter waveform as is common for ground-based TEM systems. In the frequency domain the Dighem-type multi-coil, multi-frequency systems (Fraser, 1978) are common, but recently a multi-frequency single-coil pair HEM system has become available (Won et al., 2003).

A few attempts have been made to construct a helicopter TEM (HTEM) system or a fixed-wing TEM system designed for near surface investigations. In 1982 a helicopter system referred to as the 'flying spider web' had a design similar to the INPUT system, but with the mobility of a helicopter for use in rugged terrain. However, the geometry of a transmitter on the helicopter and a towed receiver was compromised in rough topography when the helicopter could not maintain adequate forward speed. The SALTMAP system (Duncan et al., 1992) was a fixed-wing, early-time TEM system, which utilized a square transmitter waveform and 500 Hz base frequency for near-surface investigations. Unfortunately, early SALTMAP surveys had mixed results, producing inconclusive, poor-quality conductivity maps that sometimes appeared to correlate with known salt stores and sometimes not (Spies, 2001).

Only recently has the concept of a transient helicopter system come of age, and new systems are emerging making broadband measurements with a small footprint possible. The AeroTEM (Balch et al., 2002), NEWTEM (Eaton et al., 2002), Hoistem (http://www.gpx.com.au), and VTEM (Edward Morrison, Geotech Inc., personal communication) systems are designed primarily for mineral exploration – an alternative to a GEOTEM-type system better suited for geological mapping. The SkyTEM (Sørensen, K.I. and Auken, 2003) system is designed for mapping of geological structures in the near surface for groundwater and environmental investigations, and was developed as a rapid alternative to ground-based TEM surveying.

HYDROGEOPHYSICAL INVESTIGATIONS

The ground-based TEM method has been used for groundwater mapping for more than a decade. The method has been applied to ground water investigations worldwide, in a wide variety of

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geological conditions from basalts to sedimentary environments (Fitterman and Stewart 1986; Mills et al., 1988; McNeill, 1990; Sandberg and Hall, 1990; Christensen and Sørensen, 1998; Courteaud et al., 1998; Sandberg et al., 1998; Meju et al., 1999; Poulsen and Christensen, 1999; Yang et al., 1999; Sørensen et al., 2000; Hatch et al., 2002). Electrical and EM methods are particularly powerful geophysical tools for groundwater investigations because their results can be used to estimate hydraulic properties related to protective layers (Mazác et al., 1985; Kalinski et al., 1993), the chemical state of the groundwater related to contamination (Buselli et al., 1988), geothermal resources (Kirsch et al., 2003), and hydrogeological structures (Danielsen et al., 2003; Jørgensen et al., 2003). The depths of investigation for these applications range from 15 to more than 250 m. The specification of maximum depth of penetration is dependent on the target depth, which is often in the interval from 80 to 150 m for aquifer characterization. Although deeper structures are more unusual, they are not unimportant. Mapping shallow units, such as protective clay caps, requires early-time data measured from about 10 to15 μs, calculated from the beginning of ramp, until 1 to 8 ms.

In hydrogeophysical investigations, a change in response of 10–20% can be sufficient to delineate a sandy aquifer layer; in base metal mineral exploration, the target response is often more than a factor of 10 to 100 above the background response, as illustrated in Figure 1. A thin-sheet model is used to compute the response of a mineral exploration target and compared to the layered-earth response of a hydrological model. For both models the same central-loop TEM array is used. The response with the aquifer layer differs from that of the background response by a factor of approximately 1.2 or 20%, whereas the response from the mineralized sheet is roughly a factor of 100 above the background response. Hence, absolute data accuracy is crucial for hydrogeophysical investigations. The data accuracy is determined by the stability of the instrument electronics (drift), the mapping of the system transfer function (transmitter wave form, receiver low-pass filters, and timing) and the dimensional stability of the geometrical array. If not accurately designed, these factors can easily change the measured response to a factor of 1.05, which is uninterpretably small, from a factor of 1.2, which is of critical importance as illustrated by Figure 1.

Not only is high quality data necessary for interpretation of hydrogeophysical surveys, but also the surveys are often carried out in culturally developed areas. The measured earth responses can easily be distorted by coupling to man-made structures situated in close proximity to the measurement site. Coupled responses, coherent with the transmitted signal (Fitterman et al., 1990; Nekut and Eaton, 1990; Polzer et al., 1990; Qian and Boerner, 1995), must be identified in order to avoid erroneous interpretations. In general, coupled responses can be divided into two separate groups: capacitive and galvanic (Sørensen et al., 2001). Capacitively coupled responses have an oscillatory pattern and can usually be recognized in a single-site measurement. Galvanically coupled responses are more difficult to recognize, because their decay curve is similar to that of an undisturbed earth response. Therefore, dense spatial measurements are advantageous to identify and cull culturally disturbed data before interpretation. As a rule of thumb, coupled responses are avoided if the distance between the TEM array and artificial installations are larger than approximately 100 m. This distance is dependent of the overall resistivity of the subsurface.

EXPERIENCE WITH GROUND-BASED SYSTEMS

The design of the SkyTEM system is based on years of experience from numerous hydrogeophysical surveys with ground-based TEM systems.

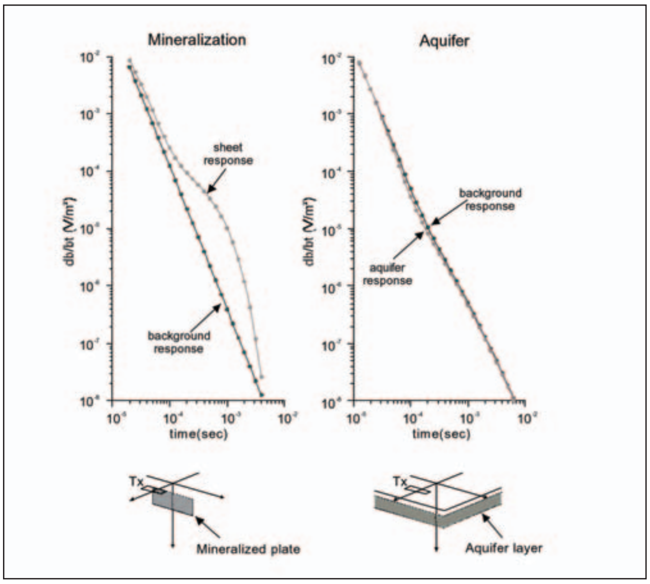

Fig. 1. Comparison of the responses of a base metal mineral exploration and a hydrological target as approximated by a vertical thin sheet and layered-earth model, respectively. The mineral exploration target is a vertical sheet measuring 90 m by 30 m at a depth of 20 m, with a conductance of 100 S, in a 100 Ω.m half space. The parameters for a three-layer hydrological model with a layer representing a sandy aquifer are: ρ_1 = 50 Ω.m, ρ_2 = 100 Ω.m, ρ_3 = 10 Ω.m, t_1 = 30 m, and t_2 = 50 m, where t is the layer thickness. The parameters for the background model (without an aquifer or a sheet) are: ρ_1 = 50 Ω.m, ρ_2 = 10 Ω.m, and t_1 = 80.

The Geonics PROTEM receiver and TEM47 transmitter is the most commonly used system for groundwater mapping in Denmark. A 40 × 40 m^2 loop transmitting 3 A provides a transmitter moment of 4800 A.m^2 for late-time measurements. For early time measurements a current of 1 A is used, reducing the transmitter moment to 1600 A.m^2 to avoid saturating the receiver and to keep the transmitter stable. The PROTEM47 system is capable of measuring the time interval from about 10 μs to about 1–4 ms under the noise conditions present in the Danish environment. The common background noise level is about 1 to 6 nV at 1 ms (with an efficient receiver area of 31.4 m^2 and a stack size of 1000). This system, in this paper referred to as conventional TEM, gives a depth of penetration of about 120 to 150 m for an average ground resistivity of 10 to 100 Ω.m. For an in-depth discussion on the depth of penetration versus background noise levels, see Spies, (1989).

The need to increase production time over single-site conventional TEM measurements led to the development of the Pulled Array Transient Electromagnetic (PATEM) system (Sørensen et al., 2000; Sørensen et al., 2004), a towed system capable of producing 10 to 15 km of continuously sampled TEM data per day. The system employed a 3 × 5 m^2 multi-turn loop with the receiver offset about 25 m from the transmitter. Transmitter and receiver were mounted on sledges pulled by a small crawler tractor.

The necessity for greater depth of penetration, which requires a higher transmitting moment, instigated further improvements to the TEM method. The HiTEM system (Auken and Sørensen (2003); Danielsen et al., 2003) uses the PROTEM receiver with a transmitter capable of putting out 75 A in a 30 × 30 m^2 loop resulting in a magnetic moment of about 67 000 A.m^2. A HiTEM measurement consists of two parts: a high-moment offset loop configuration driven by 75 A, and a low-moment, central-loop configuration using 2.4 A. The penetration depth is 250 to 300 m with the same near-surface resolution as for conventional TEM systems. In addition to the high magnetic moment, greater penetration depth is obtained because of a newly developed shielded receiver coil that has a noise level 2 to 3 times less than the coil used with conventional instrumentation. Daily production rates are comparable to those from the conventional TEM system.

The experience with the PATEM system provided the expertise necessary to develop the platform for SkyTEM. Subsequent work on the HiTEM system supplied knowledge to build a system capable of automated high-quality data acquisition. The main goals in designing the SkyTEM system were that 1) the data quality meet the same standards as that from conventional ground-based systems, and 2) the resolution of both shallow and deep Earth structures are comparable to or better than conventional ground-based systems.

SYSTEM DESIGN

The SkyTEM is a stand-alone system; no personnel other than the pilot are required on board the helicopter to operate the equipment. The transmitter and receiver coils, power supplies, laser altimeters, global positioning system (GPS), electronics, and data logger are carried as a sling load from the cargo hook of the helicopter. SkyTEM in operation is pictured in Figure 2a, with a detailed photograph of the transmitter and receiver in Figure 2b.

The selection of measurement parameters, including repetition frequency and time gates, is handled by an operator-controlled command script. The array is located using two GPS instruments. Elevation is measured using two laser altimeters mounted on the transmitter frame, measuring the height 20 times per second. Inclinometers are mounted in both the *x* and *y* directions. The measured data are averaged, reduced to data subsets (soundings), and stored together with GPS coordinates, altitude and inclination of the transmitter/receiver coils, and transmitter waveform. Transmitter waveform information (current, turn-on and turn-off ramp times) and other controlling parameters of the measuring process are recorded for each data subset, thereby ensuring high data-quality control. Erroneous readings can be identified easily during data post-processing, with the help of the comprehensive system data.

Weight is an extremely important issue with helicopter systems. Not having an operator in the helicopter reduces the total weight by 75 to 100 kg. Another important advantage of having the instrumentation outside the helicopter is that there is no need for specific licenses for the instrumentation inside the helicopter during operation, which considerably reduces the development and operation costs. A small display is temporarily mounted inside the helicopter, to allow the pilot to monitor the altitude and the inclination of the transmitter and receiver coils, and the status of the receiver/transmitter system. The transmitter loop, horizontal and 12.5 m square, is mounted on the wooden lattice frame. The total weight of the system including the electronics, power supply, GPS, and other related instruments is about 280 kg. The SkyTEM system operates continuously while the helicopter is airborne with sufficient transmitter power for about 2 hours of operation, more than the fuel endurance of the helicopter. The helicopter used now is a Eurocopter EC120 Colibri – Hummingbird.

Array Configuration and Transmitter System

The transmitter is a four-turn 12.5×12.5 m^2 square loop divided into segments to allow transmitting with a low moment using one turn, and a high moment using all four turns. The transmitter current for the low moment is about 35 A resulting in a turn-off time of about 4 μs. The high moment has a turn-off time of about 80 μs transmitting with approximately 50 A.

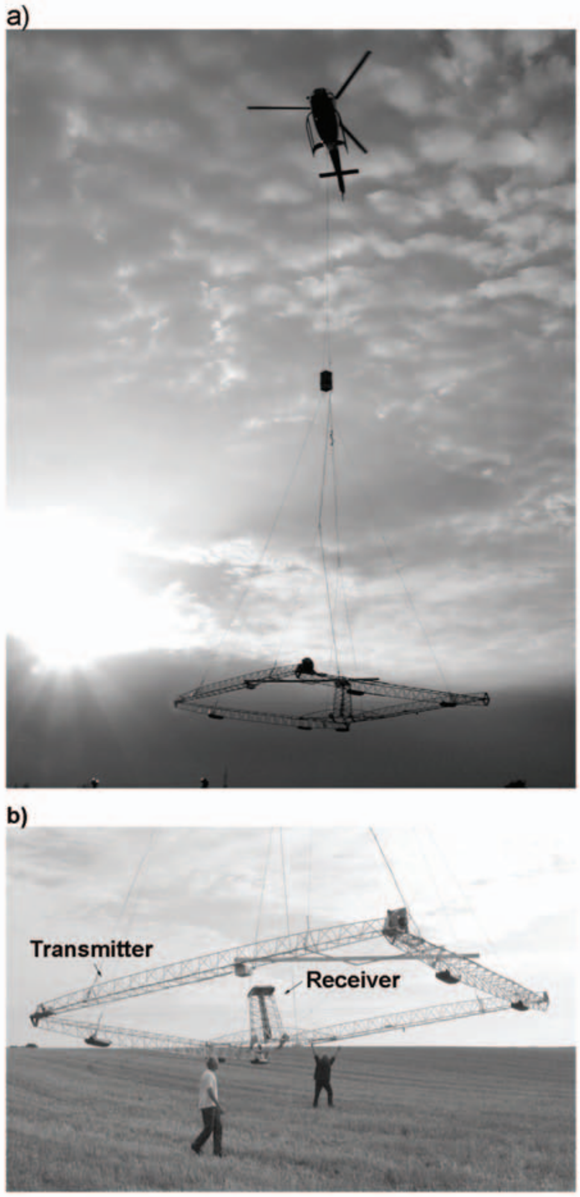

Fig. 2. (a) The SkyTEM system in operation during the spring of 2003 over Sabro, a 40 km^2 survey area west of Aarhus, Denmark. The box between the helicopter and the transmitter lattice contains computers and power supply. (b) A detailed photograph of the wooden lattice transmitter frame. The receiver coil is located at the top of the tail. The cables attached to the frame are transmitter and communication cables. Laser altimeters and angle measurement devices are mounted on the frame (not visible in the photograph).

The transmitter loop is attached to a wooden lattice frame constructed without any metal. The lattice framework ensures an extremely stiff structure resulting in rigid control of the relative position of receiver coil with respect to the transmitter. The receiver coil (dimensions 0.5×0.5 m) is located 1.5 m above the corner of the transmitter loop as shown in Figure 2b. For the SkyTEM measurement range, this configuration is practically a central-loop with a vertical offset. As analysed with one-dimensional (1D) modelling, the central-loop configuration is preferable to the offset-loop configuration because it is insensitive to near-surface resistivity variations and small changes in the transmitter-receiver separation (Danielsen et al., 2003).

The turn-off process can be divided into avalanche, or linear, and exponential regimes as shown in Figure 3. A technical description of the turn-off process is given in Appendix A.

The Receiver System

The receiver coil is a shielded, overdamped, multi-turn loop, with a first order cut-off frequency of 450 kHz. The effective receiver area is 31.4 m^2. The SkyTEM receiver system uses two embedded computers that are electrically separated. One computer controls and stores the measurements from the receiver coil while the other controls the transmitter and logs the transmitted waveform, GPS coordinates, laser altitude, and angle data. The computers communicate and synchronise using the standard TCP/IP protocol.

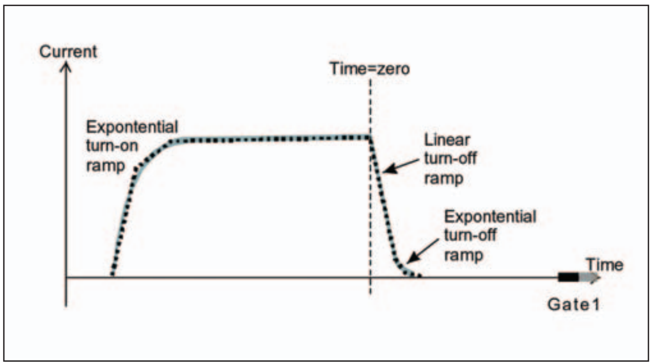

Fig. 3. The solid grey line is the theoretical transmitter waveform showing the linear and exponential regimes of turn-on and turn-off current. The piece-wise linear waveform used in modelling is shown as a black dotted line. For comparison, the location of the first gate is shown to the right.

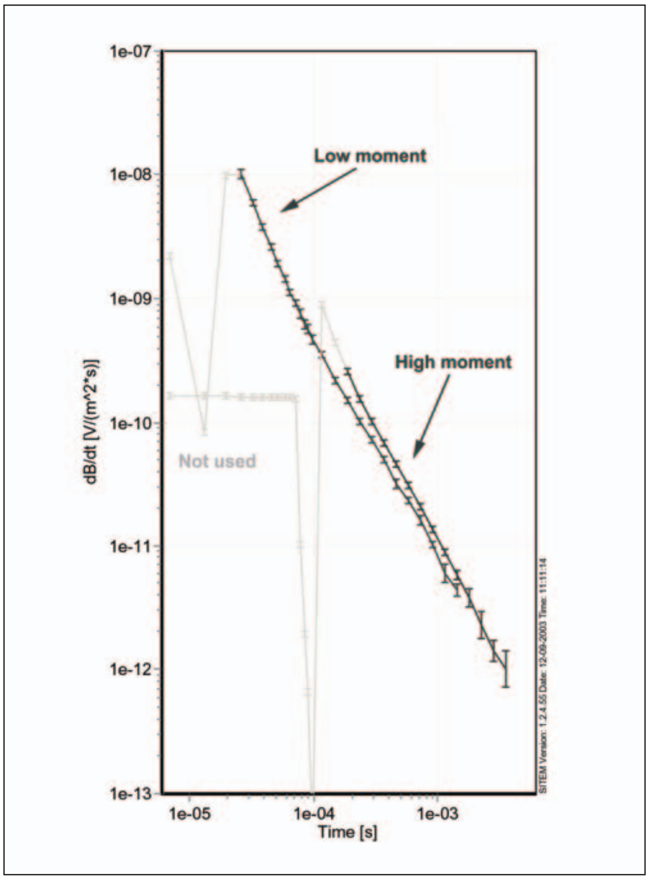

Fig. 4. A typical transient decay curve with time gates starting at the beginning of the ramp. The black curves depict the low and high moment transient decays. The curves in grey denote those parts of the data that are not used in subsequent modelling.

The receiver system uses synchronous detection with online data stacking. The stack size is normally chosen so the data quantity is reduced by a factor of 25 to 50 resulting in a manageable size dataset. The receiver integrates the incoming voltages by applying a digital controlled integrator. Characteristics of an analogue gating system followed by a synchronous detection scheme are found in Becker and Cheng (1988) and Macnae et al. (1984). The integrator output is measured in time steps of 6 µs (16 bit words) but the width of the integrator itself is controlled in time steps of 0.2 µs. The implementation of analogue rather than digital gating of the voltage is chosen to avoid aliasing effects and to condition the signals, thus reducing the quantisation errors from the analogue to digital conversion.

The incoming signal from the receiver coil is used in the time range from about 20 µs to about 4 ms as measured from the beginning of the ramp. The time gates are linearly spaced until 100 µs, after which they are logarithmically spaced with 10 gates per decade. The last measurement time depends on the base repetition frequency. The repetition frequency is typically 185 Hz and 62.5 Hz for the low and high moment, respectively. A typical decay curve is shown in Figure 4. The grey portions of the curve are data not used; the flat parts are due to a front gate. The front gate is closed during the turn-off of the current in the transmitter coil thereby preventing the strong primary signal from saturating the amplifiers in the receiver system.

Flight Speed and Altitude

The flight speed and altitude of operation are crucial parameters for resolution of the subsurface resistivity distribution. The flight speed determines the lateral average of data, and is also related to the transmitter magnetic moment. The operational flight speed of the SkyTEM system is 15 to 20 km per hour (4.1 to 5.5 m/s or 8–11 knots) resulting in a high-moment stack size of approximately 1000 transients. This is sufficient to obtain data out to 2 to 4 ms. Consequently high and low moment data segments yield an average lateral spacing of 35 to 45 m. Increasing the transmitter moment leads to a larger turn-off time, but allows greater flight speed and production rate, or an increased depth of penetration. This is because an equivalent signal-to-noise ratio can be achieved by stacking fewer data, and hence greater flight speed and production rates yield the same data quality. Furthermore, the spatial resolution of near-surface resistivity structures decreases with increasing flight altitude because the fields are upward-continued from the ground surface. Modelling has shown that a reasonable compromise between resolution and safety concerns for the helicopter and SkyTEM system is to operate so that the transmitter loop is at an altitude of 15 to 20 m, and the helicopter is at about 50 m. In forest areas, the flight height is increased by the height of the trees.

SYSTEM VERIFICATION

Before a new system can be used reliably for production, it must show that it produces valid data under normal field conditions. We will demonstrate this by showing that:

- The SkyTEM receiver compares favourably to the PROTEM47 receiver.
- High altitude measurements confirm the system response and the impact of the helicopter. The system response must be a factor of 50–100 lower than signal levels detected at operational flight heights.
- SkyTEM data are comparable to ground-based data when the transfer functions of the systems and the altitude of the SkyTEM system are taken into account.
- The system accurately repeats a sounding during standard field operation.

Comparison with the PROTEM47 Receiver

The SkyTEM and the PROTEM47 systems were compared at the Lyngby test site west of Aarhus. The Lyngby site is commonly used for calibration of TEM instruments operating in Denmark. The Lyngby 'standard sounding', made with a 40 × 40 m^2 central-loop configuration, is based on measurements from more than eight different PROTEM47 systems (Auken and Sørensen, 2003). The systems were benchmarked for repetition base frequencies of 237.5, 62.5, and 25 Hz, and transmitter currents of 1, 3, and 3 A, respectively. The standard sounding and the corresponding 1D inverted model are shown in Figure 5a, and the SkyTEM response in Figure 5b. The SkyTEM system was deployed on the ground in a 40 × 40 m^2 central-loop configuration. The difference between the two systems at early times for the high-moment response is due to significantly different turn-off ramps. The ramp effect is taken into account during modelling so this is not problematic. Apart from this exception, SkyTEM responses are within 2% of the standard sounding at all times.

High Altitude Tests – Helicopter Impact and Levelling

System noise or bias is incontrovertibly revealed when the system is taken to a very high altitude to approximate the free space response. Figure 6 shows a dataset measured at an altitude of 500 m. The grey curves are measurements with the transmitter on, which are the free space response. The black curves are measurements with the transmitter off. As seen, the grey and black curves have the same average levels and appearance. This means that the system has no significant bias and there are no significant responses from the helicopter. Hence, levelling at a high altitude is not an issue. The two curves marked low and high moment are data recorded while at normal flight heights. They are unnormalized and are shown to demonstrate actual signal levels that are encountered during a survey.

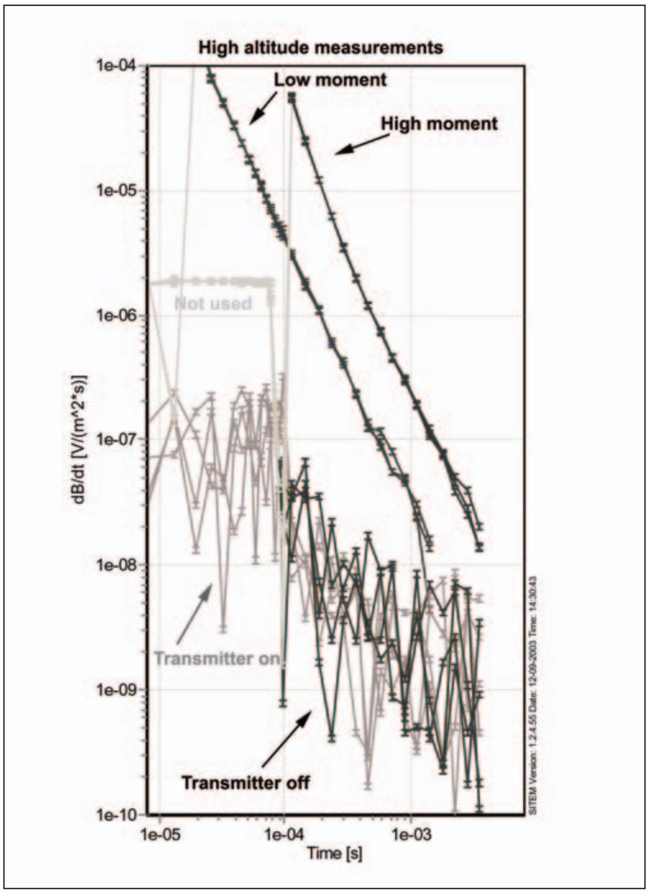

Fig. 6. Unnormalized low and high-moment sounding curves measured at an altitude of 500 m. The grey curve marked 'transmitter on' is the system response in free space. The black curve marked 'transmitter off' is the ambient noise level of the system including the helicopter. Notice there is no bias between the two, hence levelling is not required. The curves marked 'low-moment' and 'high-moment' are sounding curves recorded at normal flight height.

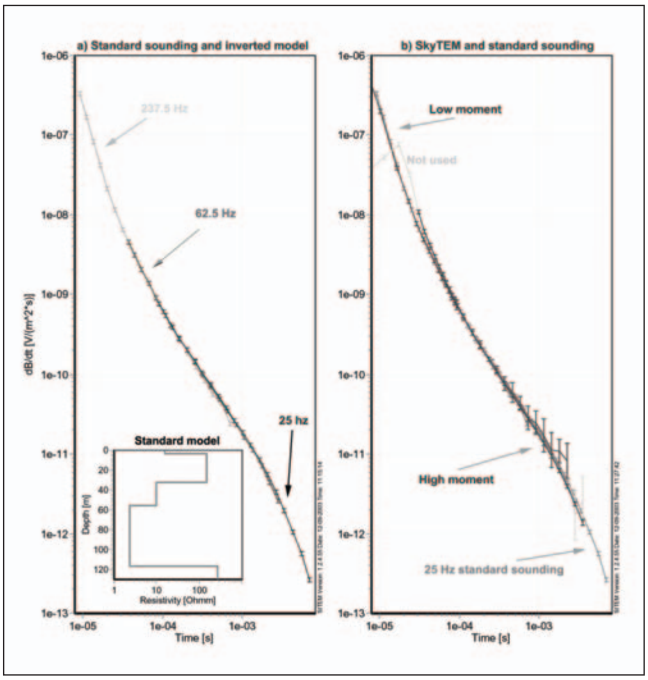

Fig. 5. The Lyngby standard sounding is made using the PROTEM47 system in a 40 × 40 m^2 central-loop configuration. (a) The three curves correspond to repetition base frequencies of 237.5 Hz, 62.5 Hz, and 25 Hz, and transmitter currents of 1, 3, and 3 A, respectively. The model is the corresponding 1D inversion result. (b) The comparable SkyTEM sounding in static mode using the same configuration as for (a).

Reproducibility of Ground Based Measurements

Data can also be acquired while the helicopter is hovering and the system is in normal operation. The test is performed with the helicopter hovering above the test site so that the transmitter is 7.5 m, 20 m, and 30 m above the ground. To compare the measurements to the standard sounding, we transform the standard sounding to a SkyTEM sounding using a two-step procedure. First the standard sounding is inverted to produce the 'standard' 1D resistivity model shown in Figure 5a. Then the SkyTEM response is calculated for the standard model with the full system transfer function, including the current waveform, the effect of the receiver coil and low pass filters in the receiver, the front gate and the system altitude. All results are of the same quality; those for an altitude of 20 m are shown in Figure 7. Except for late times when the influence of noise is pronounced, the SkyTEM data reproduce the transformed standard data within 5%.

Repeatability of Data during Field Operation

As a part of the standard field procedure, repeat data are acquired every time the helicopter refuels and gets fresh batteries, at about 1.5 hour intervals. Just before landing, the helicopter hovers with the SkyTEM system 10±1 m above the ground for about 1 minute, at a designated base site within the survey area. By comparing these datasets, we ensure that SkyTEM is operating as expected and that there is no drift in the system. Figure 8 shows the result from one day of operation at a survey south of Aarhus; the reproducibility of four soundings is better than 5%. This

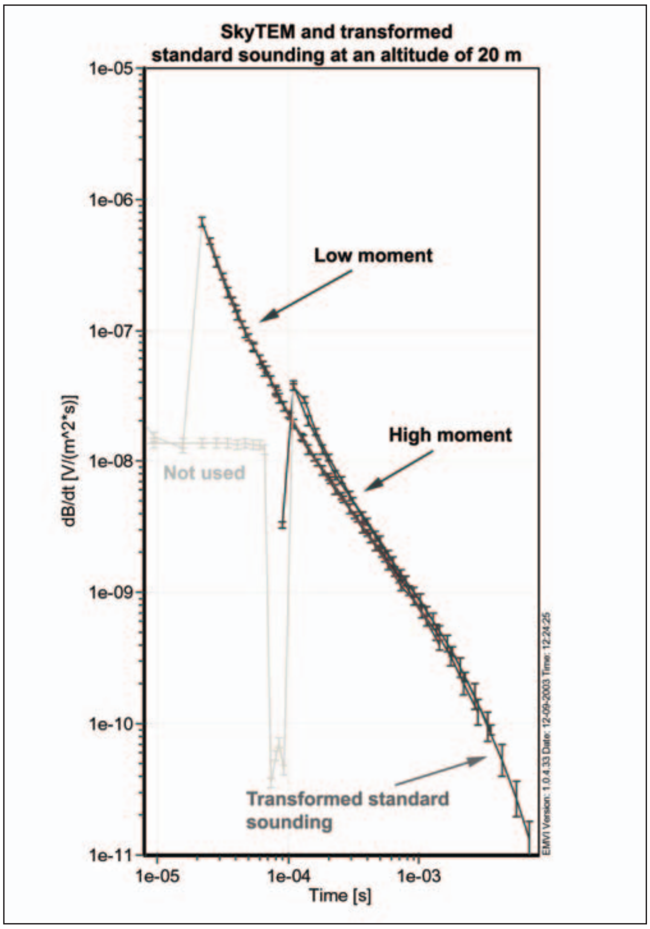

Fig. 7. Comparison of the transformed Lyngby standard sounding and SkyTEM soundings for a flight height of 20 m. The transformed standard sounding is shown in grey while the low- and high-moment SkyTEM responses are shown in black. The plot of the standard sounding is difficult to see as it is behind and a close match with the SkyTEM data.

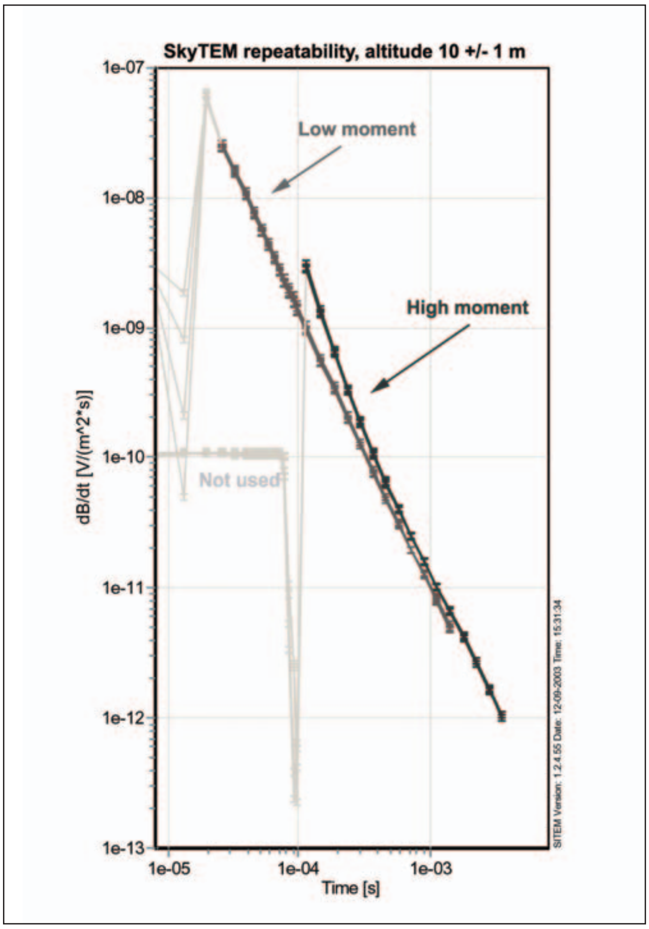

Fig. 8. Data from a base station for a survey south of Aarhus. The sounding was repeated four times within a day. Deviations of less than 5% are due to variations of ±1 m in flight height from the nominal altitude of 10 m.

amount of deviation is expected from variations in flight height altitudes due to the operation of the helicopter, not system drift.

MODELLING OF SKYTEM DATA

About 1000 SkyTEM transients are averaged into a sounding yielding data starting from 20 µs and ending at between 2 to 4 ms. With the present processing software (HydroGeophysics Group, 2001), each sounding is evaluated and data are culled if they are culturally disturbed or if they are significantly noisy. Each data point is assigned an uncertainty calculated as the standard deviation on the data stack plus another 3% to account for instrument, dimensionality, and other "unknown" effects.

The system transfer function is not deconvolved from the field data because, in our experience, deconvolution is an inherently unstable process. Instead, we have chosen to convolve our forward response in the 1D layered inversion algorithm. The transmitter waveform is applied using a piecewise-linear approximation to the ramp as shown in Figure 3a (Fitterman and Anderson, 1984). The low-pass filters are applied following Effersø et al. (1999). Filters before the front gate are modelled in the frequency domain while filters after the front gate are modelled by a convolution in the time domain. The front gate is modelled using a shifted Heaviside function in the time domain.

A sounding consists of low- and high-moment segments. Because the two segments are spatially separated (the system has moved between the soundings) the datasets are inverted with different altitudes. The flight height is included as an inversion parameter with a prior value and a standard deviation determined from the altimeters. The high- and low-moment data are inverted using Mutual Constrained Inversion (MCI) as discussed in Auken et al. (2001). This approach allows for the different flight heights and any discrepancies between the two spatially separated segments.

SURVEY RESULTS

The SkyTEM system has been used in several production surveys in 2003. The Sabro survey covers about 40 km^2 with an average line spacing of 250 m for approximately 200 line kilometres of data. The data are processed so that there is a sounding about every 40 m and inverted using the MCI approach (Auken et al., 2001) to produce resistivity depth sections. A field map is shown in Figure 9.

Aquifers in this part of the country are often associated with buried valleys incised into the low-resistivity tertiary clays (Jørgensen et al.. 2003; Auken et al., 2003; Danielsen et al., 2003). The valleys, filled with sand and gravel deposits, are the primary aquifers. The purpose of the Sabro survey is to find and delineate these buried valley structures. Figure 9 shows the survey area with individual soundings in black, powerlines and windmills in blue and the profile line in red. Figure 10 is the resistivity depth section along the profile line, as a composite of 1D MCI models. Figure 11 shows a selected sounding and the corresponding 1D inversion model.

The tertiary clay is well defined with resistivity values less than 20 Ω.m (blue colours). The profile shows two distinct buried valleys around profile locations 500 m and 8000 m. The valleys are filled with sand and gravel, indicated by resistivity values greater than 50 Ω.m (yellows and greens). The depth section shows variability in the top layer.

FURTHER DEVELOPMENTS

The SkyTEM system is the result of years of development of the PATEM and HiTEM systems, and further improvement will continue. Implementing the use of higher current, larger transmitter loops, making very early time measurements, and monitoring of the transmitted waveform in pickup coils are planned.

A system for on-the-fly inversion and quality control is under development. The system transmits system parameters, coordinates, and averaged data to a base station on the ground. At the base station the helicopter position is displayed on a GIS interface along with inverted model sections.

Efficient processing software for optimal noise suppression and laterally constrained inversion (Auken et al., 2002) for optimal model output is under development and will be put into production in the fall of 2004.

CONCLUSIONS

We have demonstrated that the newly developed SkyTEM system can efficiently acquire reliable, accurate TEM data that is comparable to that collected with a standard ground-based system for hydrogeophysical work. The wooden lattice framework makes the system lightweight and portable so that it can be shipped and used with any helicopter anywhere in the world. System parameter definitions are performed from the ground requiring only the pilot in the helicopter. The system is designed to be flown at an altitude of 10 to 20 m, with the helicopter at about 50 m, and a flight speed of 15 to 20 km per hour. This results in a high-moment stack size of approximately 1000 transients, which is sufficient to obtain data out to 2 to 4 ms, for a sounding every 40 m. Production surveys performed with SkyTEM have been successful at delineating important hydrological structures such as buried valleys.

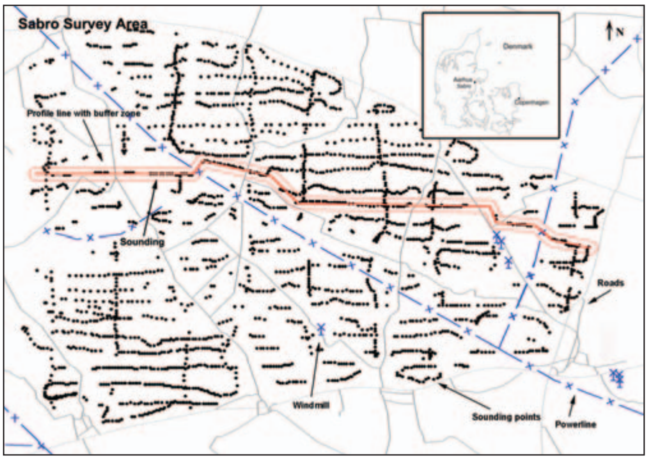

Fig. 9. Site map of the Sabro survey. The black dots show the individual soundings at the flight lines. The red line is the location of the profile shown in Figure 10. The location of a selected sounding is marked on the profile. The sounding and the inverted model are shown in Figure 11. The area is 6 × 9 km.

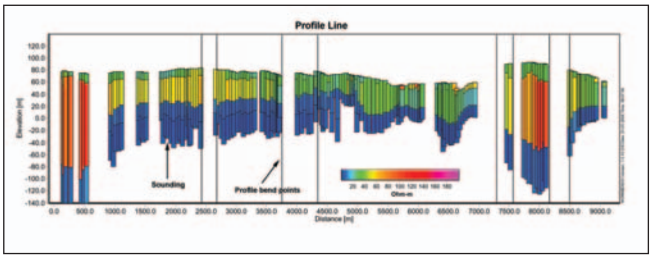

Fig. 10. Resistivity depth section. The location of a sounding is marked on the profile and shown in Figure 11.

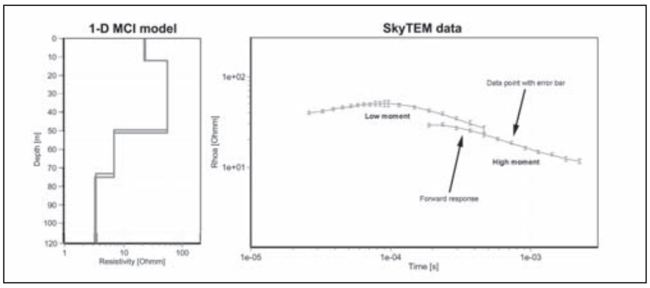

Fig. 11. A typical SkyTEM sounding, with the inverted 1D MCI model.

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APPENDIX A

The maximum voltage, V_{max}, of the transmitter is 550 V and is limited by the use of semiconductors with embedded avalanche rectifiers. The turn-off process can be divided into avalanche, or linear, and exponential regimes as shown in Figure 3. In the linear regime the magnetic moment of the transmitter coil is able to maintain the maximum voltage across the semiconductors. Changes in the current in the loop are given by

$$\frac{dI}{dt} = -\frac{V_{max}}{L}, \tag{1}$$

where dI/dt is the time derivative of the current, I, and L is the self-inductance of the loop. Because V/L is constant, the current in the avalanche regime drops linearly with time, hence the name linear. The avalanche regime ends when the magnetic energy in the loop cannot maintain the voltage. This happens at time t_e when the current reaches $I_e=V_e/R_{damp}$. The term R_{damp} is the resistance of the damping resistor, and the subscript ‘e’ refers to the exponential regime. At times greater than t_e the current drops exponentially as

$$I = I_e \exp\left[\left(t-t_e\right)\frac{R_{damp}}{L}\right]. \tag{2}$$

The turn-on current is given by

$$I = \frac{V_{bat}}{R_l}\left\{1-\exp\left[\left(t_b-t\right)\frac{R_l}{L}\right]\right\}, \tag{3}$$

where t_b is the time the current starts to turn on, R_l is sum of the loop resistance and the internal resistance of the batteries in the power supply, and V_{bat} is the battery voltage – typically 12 or 24 V.

REFERENCES

Annan, A.P., 1990, Benefits derived from the use of a fully digital transient airborne EM system: *60th Annual International Meeting, Society of Exploration Geophysicists, Expanded Abstracts*, 693–695.

Annan, A.P., Smith, R.S., Lemieux, J., O'Connell, M.D., and Pedersen, R.N., 1996, Resistive-limit, time-domain AEM apparent conductivity: *Geophysics*, **61,** 93–99.

Auken, E., and Sørensen, K.I., 2003, Large-scale TEM investigation for groundwater: *16th Geophysical Conference and Exhibition, Australian Society of Exploration Geophysicists, Extended Abstracts*.

Auken, E., Foged, N., and Sørensen, K.I., 2002, Model recognition by 1-D laterally constrained inversion of resistivity data: *Proceedings - New Technologies and Research Trends Session, 8th meeting, EEGS-ES*.

Auken, E., Pellerin, L., and Sorensen, K., 2001, Mutually constrained inversion (MCI) of electrical and electromagnetic data: *71st Annual International Meeting, Society of Exploration Geophysicists, Expanded Abstracts*, 1455–1458.

Balch, S.; Boyko, W., Black, G., and Pedersen, R., 2002, Mineral exploration with the AeroTEM system: *72nd Annual International Meeting, Society of Exploration Geophysicists, Expanded Abstracts*, 9–12.

Barringer, A.R., 1962, The INPUT electrical pulse prospecting system: *Mining Congress Journal*, **48**, 49–52.

Becker, A., and Cheng, G., 1988, Detection of repetitive electromagnetic signals: in Nabighian, M.N., (ed.), *Electromagnetic Methods in Applied Geophysics, vol. 1*: Society of Exploration Geophysicists, 443–468.

Buselli, G., Barber, C., and Zerilli, A., 1988, The mapping of groundwater contamination with TEM and DC methods: *Proceedings of the 6th Geophysical Conference, Australian Society of Exploration Geophysicists,* **19**, 240–243.

Christensen N.B., and Sørensen K.I., 1998, Surface and borehole electric and electromagnetic methods for hydrogeophysical investigations: *European Journal of Environmental and Engineering Geophysics*, **3**, 75–90.

Courteaud, M., Robineau, B., Ritz, M., and Descloitres, M., 1998, Electromagnetic mapping of subsurface formations in the lower northeast rift zone of Piton de la Fournaise Volcano: geological and hydrogeological implications: *Journal of Environmental and Engineering Geophysics*, **2**, 181–187.

Danielsen, J.E., Auken, E., and Sørensen, K.I., 2002, HiTEM - a high moment / high production TEM system: *Proceedings of the 8th European Meeting of Environmental and Engineering Geophysics*.

Danielsen, J.E., Auken, E., Jørgensen, F., Søndergaard, V., and Sørensen, K.I., 2003, The application of the Transient Electromagnetic method in hydrogeophysical surveys: *Journal of Applied Geophysics*, **53**, 181–198

Duncan, A.C., Roberts, G.P., Buselli, G., Pik, J.P., Williamson, D.R., Roocke, P.A., Thorn, R.G. and Anderson, A., 1992, SALTMAP - Airborne EM for the environment: *Exploration Geophysics*, **23**, 123–126.

Eaton, P., Anderson, B., Nilsson, B., Lauritsen, E., Queen, S., and Barnett, C., 2002, NEWTEM - A novel time-domain helicopter electromagnetic system for resistivity mapping: *72nd Annual International Meeting, Society of Exploration Geophysicists, Expanded Abstracts*, 1–4.

Effersø, F., Auken, E., and Sørensen, K.I., 1999, Inversion of band-limited TEM responses: *Geophysical Prospecting*, **47**, 551–564.

Fitterman, D.V., and Anderson, W.L., 1984, Effect of transmitter turnoff characteristics on transient soundings: *54th Annual International Meeting, Society of Exploration Geophysicists, Expanded Abstracts*, Session EM2.4.

Fitterman, D.V., and Stewart, M.T., 1986, Transient electromagnetic sounding for groundwater: *Geophysics*, **51**, 995–1005.

Fitterman, D.V., Frischknecht, F.C., Mazzella, A.T., and Anderson, W.L., 1990, Example of transient electromagnetic soundings in the presence of oil field pipes: in Ward, S.H., (ed.), *Geotechnical and Environmental Geophysics, vol. 2*: Society of Exploration Geophysicists, 79–88.

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

Fraser, D.C., 1978, Resistivity mapping with an airborne multicoil electromagnetic system, *Geophysics*, **43**, 144–172

Hatch, M., Barrett, B., Bennetts, D., Heinson, G., Telfer, A., and Roberts, C., 2002, Improved near surface mapping in groundwater studies: Application of fast-sampling time-domain EM surveying methods: *Preview*, **96**, 25–29.

HydroGeophysics Group, 2001, *SiTEM/Semdi Manual*: HydroGeophysics Group, Department of Earth Sciences, University of Aarhus.

Jørgensen, F., Sandersen, P., and Auken, E., 2003, Imaging buried valleys using the transient electromagnetic method: *Journal of Applied Geophysics*, **53**, 199–213.

Kalinski, R.J., Kelly, W.E., Bogardi, I., and Pesti, G.J., 1993, Electrical resistivity measurements to estimate travel times through unsaturated ground water protective layer: *Journal of Applied Geophysics*, **30**, 161–173.

Kirsch, R., Eberle, D., Roettger, B., Siemon, B., and Voss, W., 2003, Geothermal Planning Maps Based on Geophysical Measurements: *Proceedings of the 9th European Meeting of Environmental and Engineering Geophysics*, O-018.

Macnae, J.C., Lamontagne, Y., and West, G.F., 1984, Noise processing techniques for time-domain electromagnetic systems: *Geophysics*, **49,** 934–948.

Mazác, O., Kelly, W.E., and Landa, I., 1985, A Hydrogeophysical Model for Relations between Electrical and Hydraulic Properties of Aquifers: *Journal of Hydrology*, **79**, 1–19.

McNeill, J.D., 1990, Use of electromagnetic methods for groundwater studies: in Ward, S.H., (ed.), *Geotechnical and Environmental Geophysics, vol. 1*: Society of Exploration Geophysicists, 191–218.

Meju, M.A., Fontes, S.L., Oliveira, M.F.B., Lima, J.P.R., Ulugergerli, E.U., and Carrasquilla, A.A., 1999, Regional aquifer mapping using combined VES-TEM-AMT/EMAP methods in the semiarid eastern margin of Parnaiba Basin, Brazil: *Geophysics*, **64**, 337–356.

Mills, T., Hoekstra, P., Blohm, M. and Evans, L., 1988, Time domain electromagnetic soundings for mapping sea-water intrusion in Monterey County, California: *Ground Water*, **26**, 771–782.

Nekut, A.G., and Eaton, P.A., 1990, Effects of pipelines on EM soundings: *60th Annual International Meeting, Society of Exploration Geophysicists, Expanded Abstracts*, 491–494.

Palacky, G.J., and West, G.F., 1991, Airborne electromagnetic methods, in Nabighian, M.N., (ed.), *Electromagnetic Methods in Applied Geophysics, vol. 2***:** Society of Exploration Geophysicists, 811–879.

Palacky, G.J., 1986, A bibliography of airborne electromagnetic methods: Instrumentation, interpretation, and case history: in Palacky, G.J., (ed.), *Airborne resistivity mapping*: Geological Survey of Canada Paper 86-22, 175–180.

Peltoniemi, M., 1986, Systematic airborne electromagnetic surveys in Finland: an overview: in Palacky, G.J., (ed.), *Airborne resistivity mapping*: Geological Survey of Canada Paper 86-22, 159–167.

Polzer, B., MacNae, J., Miura, Y., and Takasugi, S., 1990, Stripping cultural conductor responses from EM data: *60th Annual International Meeting, Society of Exploration Geophysicists, Expanded Abstracts*, 487–490.

Poulsen L.H., and Christensen, N.B., 1999. Hydrogeophysical mapping with the transient electromagnetic sounding method: *European Journal of Environmental and Engineering Geophysics*, **3**, 201–220.

Qian, W., and Boerner, D.E., 1995, EM modeling of buried line conductors using an integral equation: *Geophysical Journal International*, **121**, 203–214.

Sandberg, S.K., and Hall, D.W., 1990, Geophysical investigation of an unconsolidated coastal plain aquifer system and the underlying bedrock geology in central New Jersey, in Ward, S.H., (ed.), *Geotechnical and Environmental Geophysics, vol. 2*: Society of Exploration Geophysicists, 311–320.

Sandberg, S.K., Rogers, N.T., Karp, K.E., Goodknight, C.S., and Spencer, L.F., 1998, IP and TEM for Discrimination and Resolution in Mapping Groundwater Contamination at Monument Valley: *Proceedings of the Symposium on the Application of Geophysics to Engineering and Environmental Problems*.

Smith, R.S., Fountain, D., and Allard, M., 2003, The MEGATEM fixed-wing transient EM system applied to mineral exploration: a discovery case history: *First Break*, **21**, 73–77.

Sørensen, K.I., Auken, E., Christensen, N.B., and Pellerin L., 2004, An integrated approach for hydrogeophysical investigations: New technologies and a case history: *Near-Surface Geophysics, Volume II*, Society of Exploration Geophysicists, (in press).

Sørensen, K.I., and Auken, E., 2003, New developments in high resolution airborne TEM instrumentation: *16th Geophysical Conference and Exhibition, Australian Society of Exploration Geophysicists, Extended Abstracts*.

Sørensen, K.I., Thomsen, P., Auken, E., and Pellerin, L., 2001, The Effect of Coupling in Electromagnetic Data: *Proceedings of the 7th Engineering and Environmental Geophysical Society - European Section Annual Meeting*, ELEM09.

Sørensen, K., Auken, E., and Thomsen, P., 2000, TDEM in groundwater mapping - a continuous approach: *Proceedings of the Symposium on the Application of Geophysics to Engineering and Environmental Problems*, 485–491.

Spies, B.R., 1989, Depth of investigation in electromagnetic sounding methods: *Geophysics*, **54,** 872–888. (* Erratum in *Geophysics,* **57**, 210.)

Spies, B.R., 2001, Australian Developments in Airborne Electromagnetics - From Minerals to Dryland Salinity: *ATSE Focus*, The Australian Academy of Technological Sciences and Engineering, 119**.**

Won, I.J., Oren, A., and Funak, F., 2003, GEM-2A: A Programmable Broadband Helicopter-Towed Electromagnetic Sensor: *Geophysics*, **68**, 1888-1895.

Wynn, J., Pool, D., Bultman, M., Gettings, M., and Lemieux, J., 2000, Airborne EM as a 3-D Aquifer-mapping tool: *Proceedings of the Symposium on the Application of Geophysics to Engineering and Environmental Problems*, 93–100.

Yang, C.-H., Tong, L.T., and Huang, C.-F., 1999, Combined application of DC and TEM to sea-water intrusion mapping: *Geophysics*, **64**, 417–425.