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A survey of current trends in near-surface electrical and electromagnetic methods

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ABSTRACT

Electrical and electromagnetic (E&EM) methods for near-surface investigations have undergone rapid improvements over the past few decades. Besides the traditional applications in groundwater investigations, natural-resource exploration, and geological mapping, a number of new applications have appeared. These include hazardous-waste characterization studies, precision-agriculture applications, archeological surveys, and geotechnical investigations. The inclusion of microprocessors in survey instruments, development of new interpretation algorithms, and easy access to powerful computers have supported innovation throughout the geophysical community and the E&EM community is no exception. Most notable are development of continuous-measurement systems that generate large, dense data sets efficiently. These have contributed significantly to the usefulness of E&EM methods by allowing measurements over wide areas without sacrificing lateral resolution. The availability of these luxuriant data sets in turn spurred development of interpretation algorithms, including: Laterally constrained 1D inversion as well as innovative 2D- and 3D-inversion methods. Taken together, these developments can be expected to improve the resolution and usefulness of E&EM methods and permit them to be applied economically. The trend is clearly toward dense surveying over larger areas, followed by highly automated, post-acquisition processing and interpretation to provide improved resolution of the shallow subsurface in a cost-effective manner.

INTRODUCTION

For more than half a century, electrical and electromagnetic (E&EM) methods have been important in applied geophysics, particularly for near-surface investigations. A large variety of situations are applicable to E&EM methods: general geological mapping; waste-site characterization; plume delineation; hydrogeological mapping for the spatial extent of aquifers and their degree of vulnerability; exploration for materials such as gravel, sand, limestone, and clay; geotechnical investigations of building and road construction sites; and location and identification of subsurface utilities, unexploded ordnance (UXO), and many others. The range of systems covers both those well tested and routinely applied that are commercially available in most parts of the world, and specialized systems mostly used on an experimental basis. Instruments are launched from land-based platforms, on and in the water, and in the air from airplanes and helicopters. We follow the reviews of E&EM methods in Nobes (1996), Tezkan (1999), and Pellerin (2002), and the tutorials of Fitterman and Labson (2005) and Zonge et al. (2005). Excellent overview papers have been presented about modeling and inversion of nonlinear E&EM responses and the intricacies of large-scale and ill-posed inversion problems by Oldenburg (1990, 1994) and Oldenburg and Li (2005). We present an overview of the state of the practice of E&EM methods, with some highlights of the state of the art.

The behavior of E&EM fields, governed by Maxwell's equations, spans the EM spectrum from hundreds of MHz to low frequencies approximating a direct current (DC). At high frequencies used in ground penetrating radar (GPR) or georadar method, wave propagation dominates. The GPR method will not be treated in this paper. At lower frequencies, in the quasistatic approximation, diffusion is the physical mechanism governing EM induction. At DC, the diffusion term is zero and the field is governed by the Poisson equation.

In electrical methods, resolution is determined by resistivity contrasts and scales geometrically in such a way that, generally speaking, an anomalous structure buried twice as deep must be twice as big to be detected with similar resolution. In contrast to electrical methods, resolution in EM depends on absolute resistivity rather than on resistivity contrast. Outside areas with an abundance of magnetic minerals, electrical resistivity, or the reciprocal conductivity, is

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the only parameter that varies and can be estimated from field measurements. The range of electrical resistivities found in near-surface materials can vary from 0.1 to 10,000 ohm-m. The resistivity of geological material is determined predominantly by clay content and the presence of water with dissolved, disassociated ions. Metallic responses are generally caused by anthropomorphic artifacts, such as drums and pipelines. Although not having the resolution of wavefield methods, E&EM are the only techniques in which the response is directly related to the ion content of the pore water, an indicator of the subsurface chemistry that can be correlated to important issues such as water quality.

Ambient signal noise, spatial-configuration errors, instrument malfunction, ill-determined and poorly understood recording parameters, and phenomena associated with the measuring process all contribute to data inaccuracy. The limited bandwidth of frequency- and time-domain EM equipment, the limited spatial distribution of electrode arrays in electrical methods, and discrete spatial sampling result in an insufficient data set.

Most EM data sets are inverted with 1D models, a smaller number with 2D models, and a few with 3D models, while 2D inversion is common for electrical data, and 3D is becoming more so. Data may or may not appear inconsistent if they contain features belonging to a higher dimensionality than the model used in the inversion. Resolution issues of E&EM methods along with insufficient and inconsistent data make the solution of large matrix equations involved in the inverse problem ill-conditioned. Consequently, understanding and application of regularization of the inversion process become paramount.

The resolution of model parameters is improved when the data are less noisy. Through improved accuracy of individual measurement and reduction in measuring time, more measurements are taken and stacked, enhancing accuracy. Real-time noise-reduction procedures are possible, because of the speed of modern processors. The availability of all measured data makes it possible to specify and quantify the statistical properties of the noise, and explicitly to formulate a noise model, which is extremely important for optimal and meaningful inversion.

Compared to single-site equipment, acquisition speed is greatly increased by continuous systems capable of measuring while moving on the ground, such as the multipole continuous electrical profiling (MUCEP) system (Panissod et al., 1998); the capacitively coupled OhmMapper system (Pellerin, 2003); and the pulled array transient electromagnetic system (Sørensen, 1997). Densely measured data improve the lateral resolution of the model parameters, facilitate discernment between good and bad data, and improve estimates of the dimensionality of the model needed for accurate interpretation. 2D inversion requires substantially more data than those necessary for 1D inversion. Colinear arrays are in fact a series of 2D data sets; cross-line terms may be required for a 3D data set, and hence the requirement of large data sets is even more pronounced in the case of 3D inversion.

The improved resolution obtainable by the joint inversion of two or more different data sets from the same location (Jupp and Vozoff, 1975; Raiche et al., 1985; Sandberg, 1993; Gallardo and Meju, 2003) is often jeopardized by inconsistencies between data sets. Different methods view the earth differently because of the governing physics, not necessarily because of errors in data. One way to alleviate these problems is the mutually constrained inversion (MCI) strategy of Auken et al. (2001), where each data set is inverted separately for its own model, but the model parameters of the individual models are subject to mutual constraints within certain bounds.

A problem particularly pronounced when using EM methods for environmental investigation is coupling of the transmitted field to conducting structures such as power lines, fences, buried cables, railway lines, and highway crash barriers (Sørensen et al., 2001). The transmitted field induces currents in the structures that contribute to the measured fields in a deterministic way that is not amenable to removal by filtering or stacking. Geoelectrical measurements are more robust than EM; therefore, the problem is reduced and often negligible. It is very difficult to remove the effects of coupling, making it even more important to recognize the phenomenon in data. Densely measured data and, in particular, continuous data profiles improve the chances of detecting and deleting coupled data.

The increase in computation speed has been one of the most important prerequisites for the development of 2D and 3D modeling and inversion code. However, it is not generally appreciated that improvements in capacity and speed of the computational algorithms, particularly for solving large systems of linear equations, have been as important as the increase in raw computer power. From 1980 to 1990, the efficiency of algorithms for the solution of sparse linear systems increased by a factor of 1000 — the same as the increase in raw computer speed.

ELECTRICAL METHODS

Geoelectric

The traditional categories of soundings and profiles in surface electrical measurements have to a large extent lost their meanings. With modern multi-electrode equipment and continuous systems, data are measured in many profile configurations so that lateral and vertical resistivity variation can be determined through data inversion (Buselli et al., 1990; Griffiths and Barker, 1993; Loke and Barker, 1996a, b; Carlson et al., 1999; Møller et al., 2001, Supper, 2004b; Zonge et al., 2005).

With a multi-electrode system, a large number of electrodes, typically around 100, are placed equidistantly in an array, and a computer-controlled switch box connects four electrodes to a resistivity meter. A series of configurations are measured and stored one after the other, and data are stacked until a certain noise level is reached or a certain number of measurements are attained. Many systems employ a roll-along strategy for the measurements; with an electrode spacing of 5 m, approximately 2000 m of profile can be accomplished in one day. Some multichannel systems are capable of measuring many configurations at the same time. Several systems are commercially available, and the use of multi-electrode geoelectrical measurements has increased dramatically over the past 5–10 years. Applications are as varied as mapping of aquifers and protective clay caps in hydrogeological investigations, waste site characterization, road and building foundation investigations, and archaeological studies.

Continuous systems have fixed-electrode configurations, making measurements continuously as the instrument is towed over the ground. The PACES system (Sørensen, 1996) uses galvanically coupled, steel-cylinder electrodes mounted on a tail, the MUCEP system (Panissod et al., 1998) uses spiked wheels as electrodes or capacitively coupled electrodes mounted inside plastic wheels, and the Geometrics' OhmMapper system uses capacitively coupled line electrodes (Møller, 2001). Specific problems involved in the processing and interpretation of capacitive electrode data are addressed by Shima et al. (1996), Tabbagh and Panissod (2000), and Kuras et al. (2006). The PACES system has a depth of penetration of approximately 15 m, corresponding to a Wenner configuration of 30 m. Depth of investigation for the MUCEP system is on the order of meters, while the OhmMapper system is 1 to $\sim$20 m, depending on subsurface resistivity and corresponding dipole lengths.

2D inversion is now standard with multi-electrode systems (Loke and Barker, 1996a; Oldenburg and Li, 1994; Olayinka and Yaramanci, 2000). There are several commercially available programs based on finite-difference and finite-element modeling, including a proper treatment of topography and subsurface electrodes. These programs employ a model discretized in lateral and vertical directions, and the inversion is regularized through smoothness or other constraints, some allowing specification of a priori information. The smoothness regularization is not always appropriate in environments with sharp resistivity boundaries between different geological formations. A 2D, sharp-boundary inversion similar to what was developed for the magnetotelluric (MT) problem by Smith et al. (1999) was recently developed for geoelectric data (Auken and Christiansen, 2004).

1D inversion is justified when lateral resistivity changes are small. Stitching together a series of 1D inverse models can result in a jagged-profile section that is meant to approximate a 2D section. Lately, inversion approaches have been presented (Gyulai and Ormos, 1999; Auken et al., 2005) in which the resistivity and depths to layer boundaries between adjacent 1D inverse models along a profile are constrained, often called laterally constrained inversion (LCI). These approaches represent obvious improvements, because the lateral constraints reduce the uncertainties on the model parameters resulting from equivalencies. And, borehole information can be included as a priori information.

Figure 1 is an example of a continuous vertical electrical sounding survey from Sweden carried out as part of a geotechnical investigation for road construction in connection with a filled-basin structure in bedrock. The data set was previously presented by Dahlin (1996). The data are collected using Wenner arrays, with electrode spacing between 2 m and 48 m. Figure 1b and c show 2D interpretations with a smooth model using L2 and L1 norms, respectively, (Oldenburg and Li, 1994), while Figure 1d shows a layered 2D inversion (Auken and Christiansen, 2004). All models reached a proper fit to the data. Drill-hole results are shown in all model sections. Both the L2-norm and the L1-norm inversions show the basin structure, but the layer boundaries seen in the drill holes are not identified very well, not even the depth to bedrock. The layered 2D inversion with four layers and no a priori information from drill holes clearly identifies the bedrock and the till unit on top of it in the right side of the profile. The inconsistencies in the left side of the profile between the drill-hole information and all three inversions were attributed to 3D effects by Dahlin (1996). In this case, where the geology is actually layered, the layered 2D inversion is superior to the smooth-model inversions, also providing more meaningful analysis of parameter uncertainties, as seen in Figure 1e. The resistivities of the top two layers are well resolved, as is the depth to the till layer. The depth to the bedrock is fairly well resolved. Through the introduction of a fixed number of layers in the model, the layered inversion has incorporated prior information that was not in the smooth inversion.

3D inversion has not become a standard procedure for reasons of computation resources and the necessity of very large and expensive data sets. Groundwork for 3D inversion has been done (Spitzer, 1995; Loke and Barker, 1996b), and some studies of the limits of 2D inversion in a 3D environment have been presented (Dahlin and Loke, 1997; Supper, 2004a), but more are certainly needed. In most cases, 3D data sets consist of a number of closely spaced 2D profiles. More studies regarding measurement strategies for areal coverage need to be carried out.

A question for production surveys of multi-electrode systems is which electrode configurations to measure. The choice of an electrode configuration depends upon optimizing resolution capabilities and the signal-to-noise ratio. Dahlin and Loke (1998) compare standard electrode configurations of Wenner, Schlumberger, dipole-dipole, pole-dipole, and pole-pole. The analysis in Dahlin and Zhou (2001) includes the indispensable quantitative noise model and concludes in a recommendation of gradient arrays. In Zhou and Dahlin (2003), a quantitative noise model is formulated and the effect of noise on 2D inversion is analyzed. For surveys with areal coverage intended for 3D inversion, the problem is even worse than for profile measurements (Supper, 2004a): There are 12 million electrically different, four-electrode configurations to be chosen from a set of 100 electrodes, although a large portion of these data are redundant for all practical purposes.

A promising new multi-electrode approach is presented in the system from Stummer and Maurer (2001). Hundreds of intelligent electrodes with built-in preamplifiers, analog-to-digital (A/D) converters, and digital transmission lines are deployed in the survey area, and a multichannel transmitter and receiver system carries out a series of measurements. The ambition is to realize an adaptive measuring procedure (Maurer et al., 2000; Stummer et al., 2004). Measure-

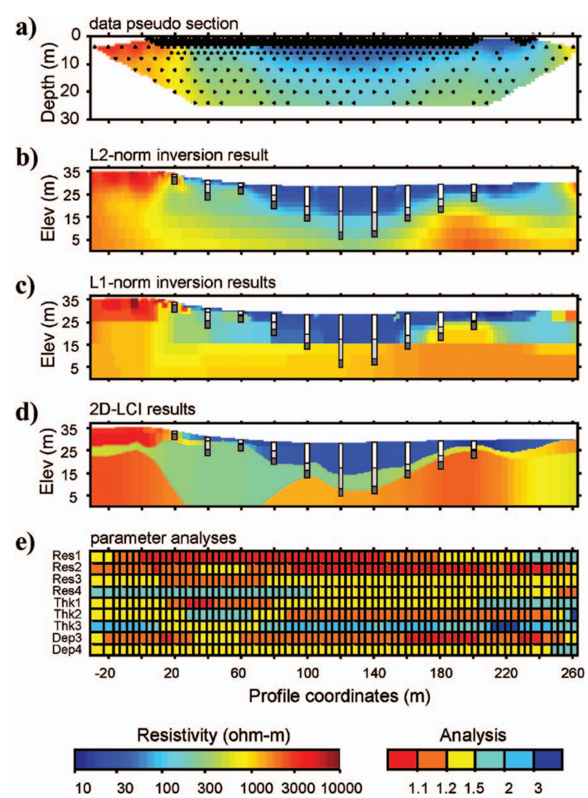

Figure 1. (a) Data pseudo section, (b) minimum structure L2-norm inversion result, (c) corresponding L1-norm inversion results, (d) 2D-LCI result with the parameter analyses in (e) The color coding of the analysis ranges from well-resolved in red to poorly resolved in blue. Lithological logs from drill holes are located at 20 m intervals from coordinate 20 to 200 m; dark colors indicate rock, light gray till and white clay.

ments are initially made on a coarse array, with subsequent configurations optimized according to the result of previous measurements. Optimal in this respect means the one that most likely will change the preconceived idea about the model. For this strategy to be viable, very fast online inversion schemes must be available to update the model estimate between measurements and to find the optimal array configuration.

Fast, approximate inversion procedures that would be applicable to the above case as well as others do exist. Li and Oldenburg (1994) present a deconvolution procedure for 3D modeling based on the Born approximation. A 2D version is presented by Møller et al. (2001), where a multichannel deconvolution approach solves the problem in the wavenumber domain, including estimates of the nonlinearity error and an automated optimal choice of regularization built on an analysis of data variability. Inversion time is less than 1 s on a modern PC for a profile with 1000 data sets, each comprising 10 configurations.

The electrical-resistivity tomography method uses strings of electrodes in closely spaced boreholes, sometimes combined with surface electrodes, to map the resistivity distribution between the boreholes. The measured data are most often interpreted with 2D, sometimes 3D, models. The method has been used to monitor remediation of subsurface contamination (Newmark et al., 1999) and to assess the integrity of subsurface barriers (Daily and Ramirez, 2000).

Permanently installed electrode arrays can be used for time-lapse imaging. Two such arrays were established at Eggborough, United Kingdom, each with 16 electrodes and 2-m spacing between each electrode. Resistivity measurements were taken, along with neutron-probe moisture content and cross-borehole radar measurements. The objective of this work was to measure moisture-content changes and to estimate the wetting-front traveltimes through the unsaturated zone of the Sherwood Sandstone, an important aquifer in the United Kingdom (Pokar, 2001).

Time-lapse resistivity inversion was performed using the algorithm of Loke and Barker (1996a), which uses the first data set as a reference model to constrain the inversion of later-time data sets (Loke, 2001). The first data set was taken on November 15, 1999, and the sections in Figure 2 show percentage changes in resistivity from November 15, 1999 to the date noted.

Data from November 1999 to September 2000 show resistivity responses according to rainfall and seasonal changes in moisture content. However, data from November 2000 to February 2001 show very high increase in resistivity (>50%) for the top 1 m of the subsurface, even though the region experienced the highest rainfall since records began in 1776. The high-intensity rainfall is thought to have leached salts from the top surface by heavy infiltration events, thus causing an increase in resistivity. Another permanently installed array on the site showed the same response for the top 1 m of the ground, indicating that the phenomenon is continuous throughout the site. The deeper layers show large decreases in resistivity, consistent with indications of a large input of water. In general, the resistivity results show a reduction in resistivity following rainfall events, which is substantiated with an increase in neutron-measured moisture content.

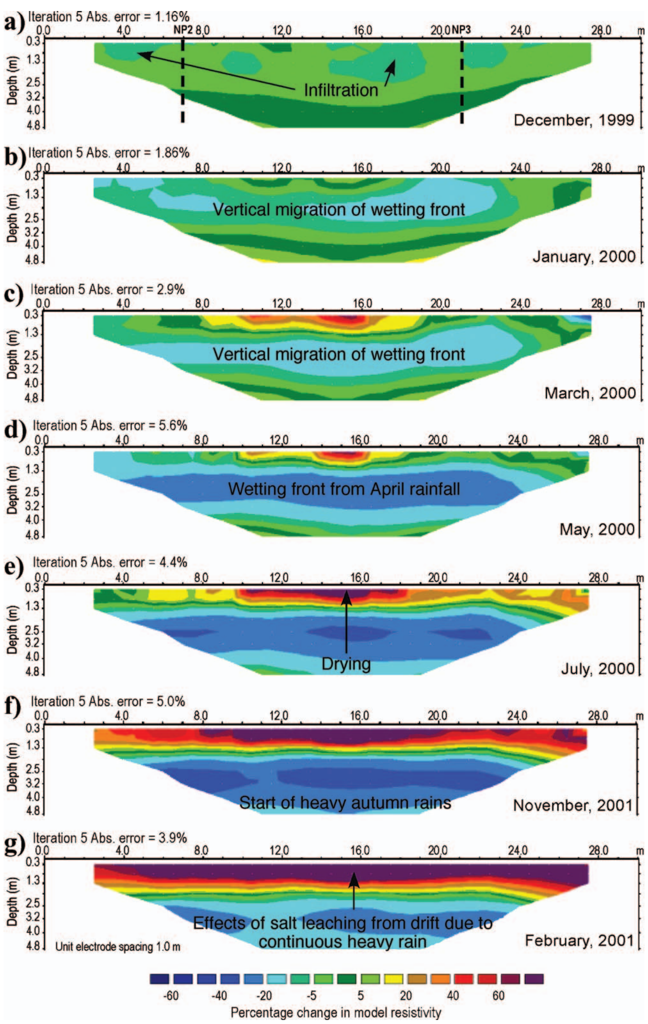

Figure 2. Percentage change in resistivity values using time-lapse, 2D inversion. The changes are from baseline data of November 15, 1999 (not shown). The wetting and drying phases tie in with nearby neutron-probe measurements.

Induced polarization

Induced polarization (IP) has traditionally been used in mineral exploration. However, it has not been used in the field of environmental geophysics to an extent matching its usefulness. In 1977, Angoran and Madden (1977) showed that IP is a powerful method for landfill characterization, and after many years of using GPR, conductivity meters, and resistivity, IP appears to be the most accurate tool of investigation (Carlson et al., 1999; Kemna et al., 2004). Vanhala et al. (1992), Vanhala and Soininen (1995), Slater and Lesmes (2002), and Draskovits and Laszlo (2005) demonstrated that contaminants can be detected and sometimes identified through their IP response.

High survey costs have been the barrier against routine use of IP, because of the use of a double system of electrodes — steel electrodes for current transmission and nonpolarizable electrodes, most often lead/lead chloride or copper/copper sulfate, for electrical-potential measurements. However, alternative solutions are emerging using smart electrodes (Stummer and Maurer, 2001), or ordinary polarizable electrodes (Dahlin et al., 2002), and new measuring strategies allowing for efficient data collection over large areas (Carlson et al., 1999; Supper et al., 1999; Denne et al., 2001). As the instrumentation improves, so has multidimensional inversion of IP data (Oldenburg and Li, 1994; Li and Oldenburg, 2000; Chen and Oldenburg, 2003; Yoshioka and Zhdanov, 2005), so that the methodology can be effectively employed.

Figure 3 shows the resistivity and IP response along a line over a waste site in Southern Sweden (Leroux and Dahlin, 2001, 2002), along with the corresponding drill-hole logs for measurements obtained with polarizable electrodes (Dahlin et al., 2002). The data from the drill holes along the line match the geophysics quite well. Whenever a high IP response was observed, waste was found. Sometimes waste was found without a corresponding IP response, but no detail was given about the nature of the waste, which can be domestic or construction waste. Measurements were taken with the modified ABEM-Lund equipment using a Wenner array with an electrode spacing of 1 m. Using a square-wave transmitter of period 4 $\times$ 1100 ms and 100- to 200-mA current, the chargeability is measured in 10 windows of 100 ms each. The first window results, represented here, are of extremely good data quality.

The fundamental principle in using polarizable electrodes is a calibration method based on measuring the polarization potential on the electrodes when no resistivity or IP response is present. Interpolation between these measurements produces the background level subtracted from the actual IP measurements. Dahlin et al. (2002) presented promising results. More studies are needed, particularly concerning the contribution to the IP response from the cables and other parts of the measuring system, but it is probably just a matter of a few years before IP data are routinely collected in multi-electrode systems. IP measurements from continuous systems are less likely to succeed, because of the motion-induced noise from the constantly varying electrochemical potentials on the potential electrodes.

ELECTROMAGNETIC METHODS

Controlled-source frequency domain

A number of configurations can be used with frequency-domain EM systems. The most common is the magnetic dipole-dipole or Slingram method that exists as multiple-frequency systems and as ground-conductivity meters (GCM), the latter operating in the low-frequency approximation. Measurements can be made of the real component in-phase with the transmitted signal and the out-of-phase or quadrature component. These methods offer the advantage that ground contact is not necessary, meaning that operation is fast, minimal personnel are required, and continuous systems can be easily implemented. They have been widely used as profiling instruments, mainly with subsequent qualitative interpretation. They are useful to locate fault zones and to map capping clays and thereby the vulnerability of aquifers (Palacky, 1991). In geotechnical investigations, Slingram/GCM surveys are constructive for delineating subsurface infrastructure and soil conditions. In recent years, an increasingly important application is location and identification of UXO.

Slingram/GCM data have a number of limitations with regard to quantitative inversion. The secondary field that carries information about subsurface conductivity is measured in the presence of the primary field, which is often orders of magnitude larger. This necessitates compensation of the primary field so that the measured in-phase component only comes from the secondary field. Accuracy of the compensation depends heavily on the transmitter-receiver distance; hence, for every transmitter-receiver separation and for every frequency, the instrument must have a compensation circuit. Instruments with coil separations of less than 60 m and a connecting cable between the transmitter and receiver are very hard to calibrate. Coil separation errors are detrimental to the accuracy of the in-phase component, unless the coil separation is so large and field conditions favorable that a good relative accuracy is obtainable; the quadrature component is relatively insensitive to separation errors (Pellerin and Alumbaugh, 1997).

The in-phase component of magnetic dipole-dipole systems is more reliably measured with fixed-boom systems, where the transmitter and receiver coils are in a rigid configuration. For practical reasons, these systems are often small. For very small coil separation, getting several meters above the ground will effectively constitute a nonconductive environment, enabling a zero calibration. For coil separations exceeding a few meters, it is cumbersome to get far enough away from the ground, consequently calibration is difficult, thereby impeding quantitative assessment of the reliability of the data. Calibration can be performed with calibration coils, but it is still a time-consuming and cumbersome process.

There is an ongoing debate about the value of having more than one frequency for geological mapping with small, fixed-boom systems. Won et al. (1996) and Huang and Won (2004) claim that differences in penetration depths are pronounced enough for multifrequency measurements to be useful. McNeill (1996) and McNeill and Bosnar (1999) maintain that for conductivity-mapping purposes, one frequency is just as good as many, because the skin depth is large compared with the coil separation for all appropriate frequencies, meaning that the sensitivity is controlled by the coil separation. However, for the purpose of detecting and identifying UXO, spectral information is important (Won, 1995).

A loop-loop system, even with a fixed boom, can be rotated and shifted for additional data acquisition. The vertical magnetic-dipole (VMD) configuration has a depth of investigation of roughly twice that of the horizontal magnetic-dipole (HMD) configuration, and the system response changes significant by measuring on the ground versus at waist height (McNeill, 1980). Hence, sounding data can be obtained with small GCM by making measurements with the VMD and HMD and by measuring at different heights.

Modern industrialized-farming practices are becoming more information intensive. The intention of precision agriculture (PA) is to

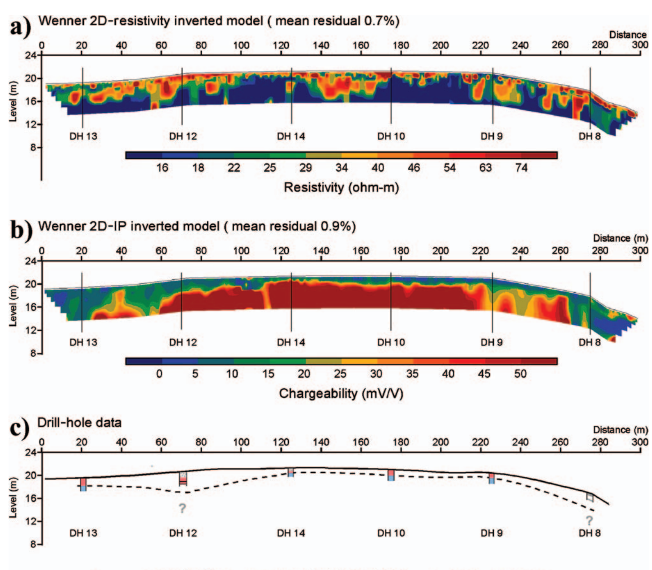

Figure 3. 2D inverse models for (a) resistivity, (b) IP models, and (c) drill-hole logs characterizing a waste site in southern Sweden.

have information on the quality of the soil to optimize sowing density, use of fertilizers and pesticides, irrigation, and time of harvest. Geophysical methods, and among these in particular noncontact EM methods such as GCM, are used increasingly to infer clay content and water saturation from conductivity measurements (Hendickx et al., 2002). PA is an interesting new field of application for dipole-dipole instrumentation, and research should be directed into developing easily calibrated systems with multiple configurations, making quantitative inversion possible.

For GCM data, the inversion problem is linear in conductivity and thereby trivial, even for large data sets. For a certain choice of model discretization and regularization, the sensitivity matrix is given and identical for all measurement sites. The matrix inversion can thus be solved once with subsequent 1D inversions consisting only in a matrix-vector product. For a system with multiple configurations, 2D inversion can be realized as a multichannel deconvolution in the wavenumber domain as in the geoelectrical case (Møller et al., 2001), using the analytically given sensitivity functions published in Pérez-Flores et al. (2001).

Helicopter EM (HEM) systems are inherently continuous, with a fixed transmitter-receiver geometry and five to six frequencies. They have been used for many applications, but find increasing use in environmental geophysics, mainly for hydrogeophysical purposes to delineate aquifers and to map their vulnerability (Fitterman and Deszcz-Pan, 1998; Roettger et al., 2005). Calibration is carried out partly on the ground before surveying and partly during flight through high-altitude measurements (Fitterman, 1998). Modern systems have reached a stability that warrants a quantitative inversion for a 1D conductivity model (Deszcz-Pan et al., 1998; Sengpiel and Siemon, 1998, 2000; Siemon, 2001), although reliable specification of the noise and leveling errors is still needed. A severe problem with the use of HEM data in urban areas is coupling of the transmitter to cultural features. Roads are often discernible on apparent-resistivity maps, particularly in the low-frequency data, because of coupling to fences, crash barriers, and buried cables. Good procedures to identify and remove disturbed data are necessary.

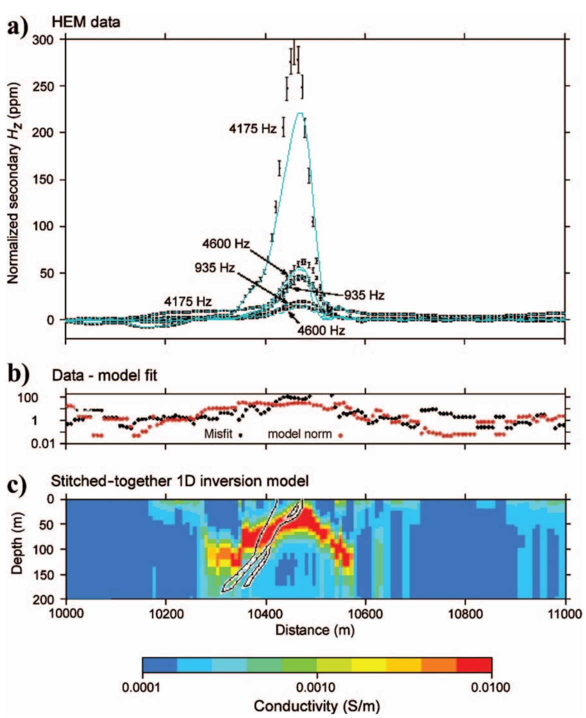

Figure 4. Stitched-together 1D inversion results of HEM data. The (a) model response is shown with (b) misfit and (c) the resulting model with the outline of the ore body from drilling.

A 2D imaging procedure has been presented by Walker (1998), and also 3D imaging algorithms are appearing (Ellis, 1998; Zhang, 2003; Zhdanov and Tartaras, 2003). However, HEM surveys use a small number of frequencies, and it is debatable how useful 2D and 3D inversion can be in light of the limited information in HEM data. Farquharson and Oldenburg (personal communication, 2002) feel that despite distortions from 2D and 3D effects, their 1D codes rather than the 3D ones are often more applicable to large, shallow data sets, resulting in 3D images of the subsurface. Figure 4 shows the results of inverting DIGHEM-type HEM data over the Heath Steele Stratmat ore deposit, New Brunswick (Farquharson et al., 2003). A series of 1D inversions are stitched together to give the images of conductivity. The outline of the ore body from drilling is shown in Figure 4c. The 1D inversion in Figure 4 included both conductivity and susceptibility (not shown), and was also published by Beard and Nyquist (1998).

The Geological Survey of Finland flies a two-frequency system with coils in the vertical coplanar configuration mounted on the wing tips of an airplane (Poikonen et al., 1998). The advantage of the system is low production cost, because of the use of a fixed-wing platform instead of a helicopter. Beamish and Mattsson (2001) successfully carried out a quantitative inversion, but there is very limited information with only two frequencies measured.

Plane wave

In the depth range of interest for environmental purposes, the relevant plane-wave methods are radiomagnetotellurics (RMT) with depths of investigation from meters to tens of meters, audiomagnetotellurics, and controlled-source audiomagnetotellurics (CSAMT) for depths greater than 10 m. The RMT method, making use of EM fields from radio transmitters and ambient signals operating in the frequency range between 10 kHz (VLF transmitters) and 500 kHz (AM transmitters), has been used for mapping waste sites and other contaminated areas (Zacher et al., 1996; Tezkan et al., 2000). The CSAMT method has been applied to deeper-lying hydrological- and mineral-exploration targets (Zonge and Hughes, 1991; McPhee et al., 2005).

Traditional CSAMT systems often use a single-grounded electrical source for scalar measurements; the Stratagem® system by Geometrics uses an orthogonal magnetic source for tensor measurements. The controlled source transmits higher frequencies where natural signal strength is low. Fields from a controlled source can be regarded as planes at distances greater than roughly three skin depths from the source, thereby putting a constraint on the transmitter-receiver separation (Zonge and Hughes, 1991). At the University of Cologne, a Swiss-built scalar instrument capable of receiving four frequencies has been used for a number of years for waste-site characterization and contaminant studies. The EnviroMT system, jointly built by the University of Uppsala, Sweden, and Metronix, Germany, is a tensor system that measures the vertical magnetic component, to a maximum frequency of 250 kHz. A controlled source is used for the frequencies from 10 kHz to 1 kHz (Pedersen et al., 2006). For years, there have been rumors that VLF transmitters, traditionally used for submarine communication, are being closed because of the use of satellites, leaving the low-frequency band to be acquired through the use of controlled source. However, there has been no evidence that this will happen in the foreseeable future.

The plane-wave methods have the significant advantage of being able to readily use the multidimensional modeling that has been well developed in the MT community. Modeling and inversion capabilities are more developed than for controlled-source method, because of the smaller computation demands and greater use. Presently, there are several 2D inversion codes (de Groot-Hedlin and Constable, 1990; Smith and Booker, 1991; Smith et al., 1999; Rodi and Mackie, 2001). 3D inversion codes are beginning to be used (Newman and Alumbaugh, 1999; Mackie et al., 2001; Sasaki, 2001; Haber et al., 2004), but of course it is time consuming and expensive to collect a data set that justifies 3D inversion.

A RMT data set acquired in scalar mode over a buried waste site was successfully analyzed using a 3D MT inversion scheme, employing nonlinear conjugate gradients (Newman et al., 2003). Over 4800 data points collected on multiple-measurement profiles were simultaneously inverted. The resulting image clearly detects the buried waste and where receiver profiles cross pit boundaries, thus mapping the lateral extent of the pit. However, findings show that the base of the pit is not well resolved, and depends upon the starting model used to launch the inversion, as can be seen in Figure 5. The image in Figure 5a employed a two-layer starting model, while that in Figure 5b had a homogeneous half space. Because of this problem, critical information on whether contamination is leaching into a resistive gravel bed lining the base of the pit, as well as the deeper geological horizons consisting of brown coal, clay, and tertiary sands is inconclusive. Nevertheless, by incorporating within the inversion process a priori information of the background media that is host to the waste, sharper images of the base of the pit are obtained, which are in good agreement with borehole data. Findings also indicate that 2D MT interpretation can produce overestimates on the pit's depth extent, which may lead to the erroneous conclusion that the geological horizons beneath the pit have been contaminated.

The RMT method is an obvious candidate for a continuous system. No ground contact is needed to measure the magnetic fields, and the electrical fields, could be measured with capacitively or galvanically coupled electrodes.

Transient electromagnetics

The transient electromagnetic method (TEM) has gained increasing popularity over the past decade. Many portable systems for single-site measurements are commercially available and developed by academic research groups. Being an inductive method, it is particularly good at mapping the depth to and extent of good conductors, and relatively poor at distinguishing conductivity contrasts in the low conductivity range. Clay and salt-water intrusion constitute conductive features of special interest in aquifer delineation. One should not expect to distinguish between the unsaturated and saturated zones, but useful information about the conductivity structure and the quality of the aquifer can be gained. Hence, the method is well known in hydrogeophysical investigations to characterize aquifers (Fitterman and Stewart, 1986; Hoekstra and Blohm, 1990; Sørensen et al., 2005).

With the TEM method, there is a trade-off between a small-moment transmitter with a short turn-off time for good resolution of the near surface, and a large-moment transmitter with a longer turn-off time with greater depth of penetration. The central-loop configuration is the most stable for early-time measurements, because of its insensitivity to configuration inaccuracies and the high signal level. For a high-moment transmitter, the configuration is sensitive to small currents remaining in the transmitter loop after turn-off and IP effects. The offset configuration is sensitive to transmitter-receiver separation inaccuracies at early times, but not at late times, and it is rather insensitive to IP effects.

A continuous-TEM system was designed with alternating small and large moments (Sørensen, 1997; Danielsen et al., 2002). A sounding has two spatially separated components corresponding to the two configurations, which have different sensitivities to the near-surface and array geometry. Inconsistencies may arise between the two data sets, so the MCI approach (Auken et al., 2001) is used to invert the data. The MCI algorithm simultaneously inverts the high- and low-moment data sets and produces two 1D models that are bound through a constraint matrix. The constraints allow for a quantitative discrepancy between the two data sets, while producing two models that, for practical purposes, are identical.

In autumn 1999 and spring 2000, a TEM survey was undertaken in a 50 km^2 area east of Skjød, Denmark, with special focus on potential groundwater resources and hydraulic properties (Danielsen et al., 2003). The survey area of approximately 40 km^2 was covered by the equivalent of 40 $\times$ 40 central-loop TEM soundings. Data were inverted using the parameterized 1D approach of Effersø et al. (1999). There were no topographic, geomorphologic, or geological data to indicate the presence of a buried valley system, which was re-

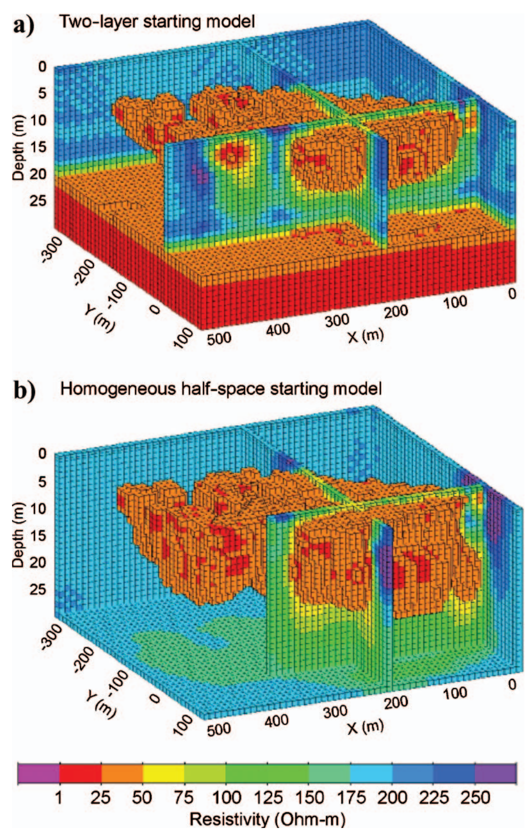

Figure 5. 3D RMT inverse model of the waste pit for two different starting models: (a) two layers and (b) homogeneous half-space. Resistivities greater than 50 ohm-m were rendered invisible, except along selected cross sections.

vealed solely by the TEM survey. Figure 6 is a map of the elevation of the conductive Tertiary clay, which defines the basal layer with resistivity below 15 ohm-m in the 1D inverse models. Two main features are apparent, one striking north-south and the other southeast-northwest. The steep part of the buried valley descends from approximately 35 m above sea level (yellow colors) to approximately 50 m below sea level (green-blue colors) over a few hundred meters.

Airborne-TEM methods are finding increasing use in environmental investigations, often for hydrogeological investigations (Lane et al., 2001; Sørensen and Auken, 2004). Compared with ground-based TEM, the near-surface resolution and the lateral resolution are inferior, and problems with coupling to cultural conductors are more serious. However, the productivity is unrivaled, and the method is well suited for investigations in remote and inaccessible areas. Recent analyses of the resolution capabilities of airborne methods suggest that the information content in data is sufficient to resolve three to five parameters in a 1D inversion (Christiansen and Christensen, 2003).

A few attempts have been made to construct a HTEM system or a fixed-wing TEM system designed for near-surface investigations. In 1982, a helicopter INPUT system (Barringer, 1962), 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 (Fountain, 1998). 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 was a fixed-wing, early-time TEM system, which utilized a square transmitter waveform and 500-Hz base frequency for near-surface investigations. Unfortunately, SALTMAP surveys had mixed results for a while, 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 HTEM system come of age, and new systems are emerging that make 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 systems are designed primarily for mineral exploration as an

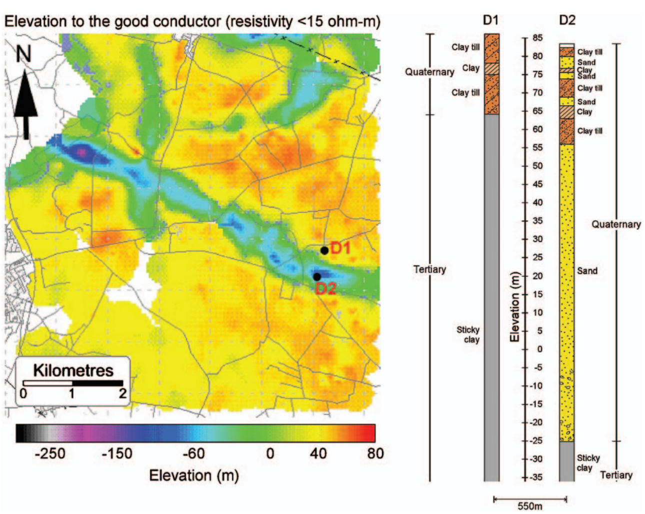

Figure 6. The elevation of the deep conductive layer constructed from 1D inverse TEM models as defined by bottom layer having resistivity values below 15 ohm-m, which is interpreted as the top of the Tertiary clay.

alternative to a GEOTEM-type system for more mobility in rugged terrain. The SkyTEM (Sørensen and Auken, 2004) system is designed for mapping of geological structures in the near surface for groundwater and environmental investigations.

For large airborne or continuous-TEM data sets, 1D inversion is time consuming, but realizable (Christiansen and Christensen, 2003). Approximate imaging algorithms enable a rapid overview of the results (Macnae and Lamontagne, 1987; Macnae et al., 1991; Stolz and Macnae, 1997, 1998; Wolfgram and Karlik, 1995; Christensen, 2002). An approximate image can also be used as a starting model for a subsequent nonlinear inversion. The approach of laterally constrained, stitched-together 1D models is applicable for profile-oriented TEM data (Auken et al., 2000) and for airborne data (Auken et al., 2004). Wolfgram et al. (2003) demonstrate the use of approximate 2D imaging on airborne GEOTEM data, but full nonlinear inversion with 2D and 3D models is still prohibitively time consuming.

The issue of an accurate description of recording parameters in TEM soundings is very important. It has been demonstrated that the inherent filtering of TEM receiver systems caused by the band-limited behavior of induction coils and feedback amplifiers must be taken into account when inverting EM data (Effersø et al., 1999). Neglecting these aspects will lead to erroneous interpretations. Experiments with user-selected and stable low-pass filtering can improve the resolution of the model parameters, especially in the near surface (Auken et al., 2000).

The VETEM system (very early time EM) developed by the U.S. Geological Survey was an attempt to construct a TEM system capable of measuring in the nanoseconds range. The VETEM responses span the region between the quasistatic approximation and wave propagation so the data bear information on electrical permittivity and electrical conductivity. Quantitative modeling of the measured responses has turned out to be difficult. However, field investigations with dense areal coverage have revealed many details not obtainable by EM or GPR systems (Wright et al., 2000).

A transient system for UXO and utility detection has been developed by Zonge Engineering (Carlson and Zonge, 2003). Figure 7a shows a plan view of the horizontal vectors (Hx, Hy) from a fast-turnoff, cart-mounted TEM system, the Zonge NanoTEM system, at approximately 1 μs after transmitter turn-off. The northeast-southwest trending survey lines crossed a buried north-south metallic pipeline (linear feature A) and a buried metal plate covering a septic tank (feature B). In background areas, the horizontal component of the field is very small, as expected, but when approaching and receding from a target, the horizontal component increases in amplitude and flips polarity as the TEM system crosses the target. This polarity change can be used to identify features in random-walk type surveys. Figure 7b shows a portion of a large grid at Fort Ord, at the Seaside Site, Grid H-8. The vectors are again the horizontal field (Hx, Hy) at about 1 μs after transmitter turn-off, and the colors of the vectors are correlated to the Hx magnitude. Again, when there are no anomalies, the horizontal component is near zero; approaching and on top of the target, the horizontal field looks very much like model responses from small metallic features.

OTHER METHODS

There are a number of methods outside the mainstream of E&EM environmental geophysics that merit comment. Magnetic resonance sounding is a fairly new method for use in groundwater exploration and aquifer characterization. The principle of the surface nuclear-magnetic resonance (SNMR) method is to electromagnetically excite the precession of protons — hydrogen nuclei — about the direction of the earth's magnetic field by transmitting the Lamor frequency with a large transmitter loop and a high current, turn off the transmitter, then measure the decaying magnetic fields at the Lamor frequency as equilibrium is reestablished. Only a few soundings can be made in one day because of the low signal-to-noise ratio of the measurements and the long stacking times.

A 1D inversion of SNMR data is uncomplicated, and the primary parameter obtained through inversion is the density of hydrogen atoms, which is directly related to the water content. The resistivity structure of the earth is needed to unambiguously interpret the SNMR data so that this method is coupled with TEM. The potential of the SNMR method lies in the fact that it is the only geophysical method that will directly determine the water content, and there is slowly growing interest in the method. A parameter related to the grain-size distribution can also be obtained if data are good. Use of the SNMR method in hydrogeological investigations is reported in Yaramanci et al. (1999) and in special issues of the Journal of Applied Geophysics (2002, vol. 50).

In Figure 8, the results of a combined TEM and SNMR survey at the Ash Meadows National Wildlife Refuge, Nevada, are illustrated (Abraham et al., 2003). Ash Meadows is a desert oasis supplied by springs. The TEM inversion results reveal a broken resistive layer, and the resistivity model is used in the inversion of the SNMR data. Several water-rich zones are indicated by the inversion of the SNMR data. The results are used in an improved hydrogeological model for the area.

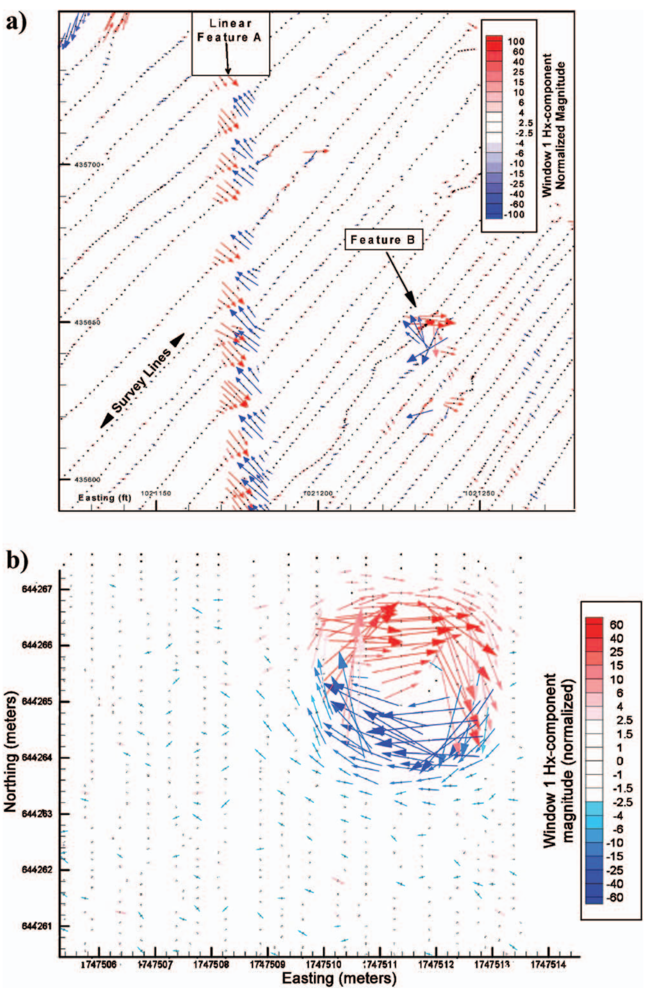

Figure 7. Plan view of the horizontal vectors (Hx, Hy) from a fast-turnoff, cart-mounted TEM system at approximately 1 ms after transmitter turn-off. (a) The northeast-southwest trending survey lines crossed a buried north-south metallic pipeline (linear feature A) and a buried metal plate covering a septic tank (feature B). (b) A portion of a large grid at Fort Ord, California, seaside site, Grid H-8.

THE FUTURE

The front end of any geophysical system is the sensor: Galvanic and capacitive electrodes for electrical systems and induction coils for measurement of the magnetic field in EM systems. The principles of the sensors have remained unchanged for a long time; however, refinements in low-noise electronic amplification and filtering have improved performance substantially. Clerc et al. (1998) and Lu and Macnae (1998) made comparative studies of electrodes for geoelectrical measurements, but there must be room for radical improvements. Why do we not have nonpolarizable electrodes in a material as mechanically sturdy as steel, so we can easily measure IP effect in the same measuring procedure as electrical resistivity? This might be attainable through closer collaboration with solid-state physicists, who have produced many other smart materials.

We should also look into the subject of tiny magnetic sensors based on some quantum mechanical effect with sensitivity and dynamic range sufficient to measure geophysical fields. The magnetic-strip sensors based on the magnetic Hall effect are promising, but improvements are still needed. Small, lightweight sensors could make it possible to have multiple receivers mounted on a variety of

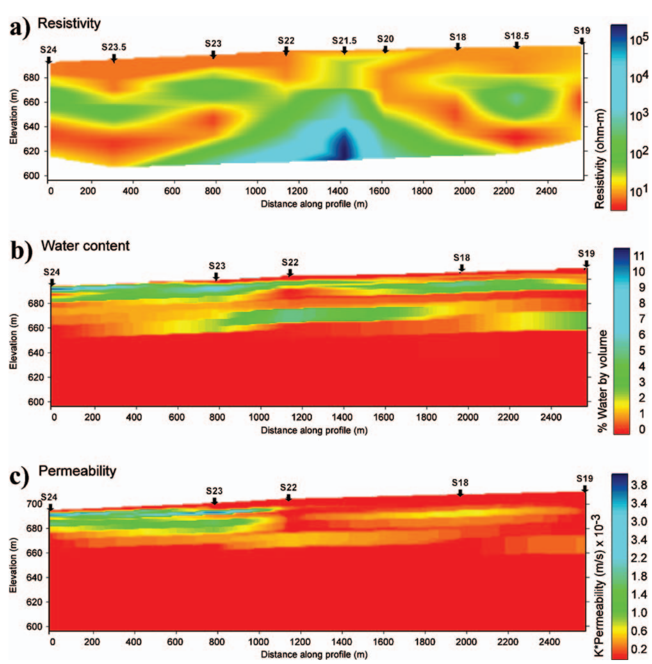

Figure 8. Results of TDEM and SNMR soundings along the east-west profile at Ash Meadows, Nevada: (a) Inverted TDEM data in Log10 (resistivity), (b) SNMR percent water content, and (c) SNMR permeability (m/s).

platforms, such as small model aircraft collecting a very dense data set over an area exited by a transmitter loop.

Amplification, filtering, and A/D conversion have seen significant improvement during the past decades. There are 24-bit A/D converters with sampling rates higher than 1 MHz, though still costly. We will witness further improvements that will meet the needs of geophysical equipment. Processing speed and storage capacity will also increase, enhancing data acquisition, processing, and interpretation.

To improve interpretation, data quality must be improved. Hence, we need to know the noise character under different measuring conditions and to formulate quantitative noise models for optimal inversion. An emerging field of research is noise-adaptive filtering, where the character of the noise is analyzed in real time so that optimal noise-reduction schemes can be applied. However, there is still a need for quantitative assessment of the noise characteristics of present measuring procedures, and studies within this field should be encouraged. In many cases, slightly changing field procedures could accomplish much. As an example, in airborne TEM, measurements of the entire time series instead of just the mean of the transmitted field at high altitudes would enable an error estimate on the primary field. The primary field is subsequently subtracted from all measurements, so its variability contributes to the data error. Also, measuring the time series at normal recording altitude with the transmitter turned off would allow an estimate of the ambient noise level at the recording site. These simple procedures could quantify the noise on the on-time as well as the off-time channels.

System configuration and the set of frequencies or delay times are most often fixed, but an in-field, adaptive choice of noise processing, filtering, and stacking obviously would be able to produce improvements. For distributed systems with a wide range of possible configuration, such as multi-electrode systems, one could envisage an adaptive measuring procedure. After initially measuring a sparse grid, the optimal configuration to be measured next could be chosen.

Fixed-wing, airborne-TEM platforms fly too high and too fast, resulting in poor vertical and lateral resolution in near-surface investigations. The aim must be to construct an airborne system with the same near-surface resolution as ground-based systems. The emerging technologies with helicopter-borne TEM systems point in the right direction.

We need to see development of 3D visualization options. E&EM methods, in particular airborne and other continuous methods, collect very large data sets and cover large areas, and there is a need for interactive 3D presentation techniques similar to those developed for seismic presentations, which will allow a number of people to see and discuss the data and the results of the interpretations. Such presentation techniques would also be very useful in the interactive process of inversion, evaluation, and repeated inversion with other a priori bounds and regularizations. However, most near-surface geophysical investigations are carried out within small budgets, so besides the projection chambers of 3D visualization techniques, solutions applicable on an ordinary PC would be most welcome.

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