Electrical and EM methods, 1980-2005

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The last two decades saw major advances in data collection, processing, and interpretation of electrical and EM data. Lower transmitter frequencies for airborne time-domain EM systems have made possible surveys in areas where conductive cover previously screened basement conductors. As with every other branch of technology, the evolving speed of the silicon chip and of streaming data to hard disk has revolutionized data collection and noise reduction processing. Major advances have been made on increasing the signal-to-noise ratios in ground EM data acquisition systems. Full-waveform recording and the use of multiple receivers are becoming common for ground EM techniques. Previously intractable 2D and 3D data inversions are now slowly becoming available. Finally, controlled-source EM techniques are now being used to detect and characterize hydrocarbon-bearing reservoirs in deepwater areas.

A complete description of significant advances made in these areas is beyond the scope of this review. While most will be only mentioned, a few significant developments will be treated in greater detail.

Induced polarization method. Development of smooth-model 2D induced polarization (IP) inversion is one of the most visible changes to geophysical interpretation of the last 40 years and is now routinely applied to dipole-dipole and pole-dipole IP data. The ability to view resistivity and IP parameters in section rather than pseudosection view has revolutionized interpretation. Although computation speed has improved significantly using the numerically efficient conjugate-gradient method (replacing the older Gauss-Newton approach), extension of inversion methodology to 3D is limited by two factors. First, computation for 3D models is too slow for routine use as yet. Second, instrumentation has not fully kept pace, and data acquisition is still usually limited to linear profiles. The MIMDAS system (Sheard, 1998) with its distributed data acquisition modules provides a means for 3D acquisition of IP data. Given high-quality 3D data, the impact of 3D IP inversion over the next decade may be comparable to that from 2D inversion over the last.

A technique, still in development stage, and mostly suitable for surveying in arid areas where ground contact with electrodes becomes extremely difficult, was proposed by Gasperikova and Morrison (2001) who used natural fields to make IP measurements without using grounded electrodes. The method is based on monitoring changes with frequency in the response of a polarizable body at low frequencies for which the measured electric field becomes frequency-dependent and phase-shifted with respect to a reference field. Macnae and Yang (2000) also showed the successful use of guarding to allow capacitive electrodes to be used for resistivity measurements at frequencies down to 0.1 Hz, but these sensors proved too noisy for reliable IP data collection.

Ground EM methods. In ground electromagnetic surveys, the major advances have been in moving toward full-waveform recording, moving toward increasing signal-to-noise ratio, and the simultaneous use of multiple receivers. TEM instrumentation is also becoming available for shallow (upper 10 m) studies at mine sites and for geotechnical and environmental applications. Parallel advances have been made using radio-frequency instrumentation to map very shallow depths. These new applications have been made possible by advances in switching and digital acquisition technology which enable very fast turn-off transmitters (order 10 μs) and high-speed sampling of the first 100 μs of the receiver waveform.

The magnetotelluric (MT) and controlled-source audio magnetotelluric (CSAMT) techniques have progressed in terms of statics removal and notably in inversion methodologies. The use of remote monitoring stations in both MT and IP surveys has improved data quality. In principle MT and CSAMT methods offer greater depth penetration than conventional ground TEM methods, but it appears that they have not yet achieved the resolution necessary to compete with TEM methods in mineral exploration.

Two independent major advances have been made recently that have had a dramatic effect on increasing signal-to-noise ratios in ground EM data acquisition. Each has independently led to about an order of magnitude improvement in signal-to-noise ratios. The first is the development of Squids, now in routine use as magnetic component sensors in mineral exploration, and the second is the development of distributed array acquisition systems.

Superconducting quantum interference devices (Squids) operating at low temperatures are low-noise magnetic field sensors in common use in medical nuclear magnetic resonance scanning devices. Anglo-American, in conjunction with IPHT, has developed a robust low-temperature Squid (LTS) sensor for geophysical exploration, and a group at CSIRO in Australia has developed a geophysical High Temperature Squid (HTS) sensor. These are B rather than dB/dt sensors, and comparisons with coil sensors are therefore complicated by considerations of the effect of the time derivative. To generalize, when compared to dB/dt sensors, B field sensors have reduced dynamic range, better low-frequency sensitivity, reduced effect of spherics, and produce anomalies from targets under conductive cover that show up significantly earlier in delay time. To clearly exhibit the advantages of superconducting sensors, we present a comparison of Squid data with a "state of the art," room temperature fluxgate sensor (Figure 1).

The averaging times required to reduce white noise to produce stacked data of equal signal/noise ratio would be in the ratio of the squares of the standard deviations; and thus be in the ratio 1 (LTS) to 28 (HTS) to 870 (Fluxgate). According to this, an average at one station of just 1 minute of LTS data would have the same precision as half an hour of HTS data or 14.5 hours of Fluxgate data. Averaging of course can only improve "random" noise and will not correct for any bias or systematic noise present in data. Further, sensor noise may not be the limiting factor near power lines or when nearby thunderstorm activity dominates the noise spectrum.

Comparing Squid data to conventional coil data in field trials has demonstrated robust and easy detection by LTS and HTS sensors of several excellent conductors, located in Western Australia under thick cover exceeding 150 siemens in total conductance. These targets are very challenging for coil sensors.

The challenge of obtaining useful TEM data in or near operating mines, where power-line and mine-communication electromagnetic noise severely limit the usefulness of exploration instruments, has led to the development of a number of systems with distributed data acquisition modules. Western Mining, recently acquired by BHP Billiton, and Electromagnetic Imaging Technology have developed a wireless, distributed array data acquisition system named Geoferret. This system relies on a node consisting of a remotely programmable (via PDA), self-contained sensor and 24-bit data recorder. The sensor itself is a very low-impedance aluminum wire coil that, due to its low internal resistance, has lower noise than copper coils of equal weight. The field operation involves first setting up an operating fixed transmitter. Each node is then laid out in turn at successive stations along a survey line, and left to acquire data. After the last of about 20 stations is installed, the operator returns to the first station and moves it across to the next survey line, followed by the others in succession.

Adjacent stations have simultaneous data acquisition more than 90% of the time, which can lead to significant noise reduction, particularly if processing takes advantage of the fact that remote noise sources will tend to have virtually identical responses at adjacent sensors on uniform ground. Because of the reduced sensor impedance, increased averaging time and the use of essentially simultaneous data acquisition, Geoferret has led to an order of magnitude reduction in noise levels in routine data acquisition.

The "MIMDAS" digital acquisition system, developed by Mt. Isa Mines (MIM Exploration), typically deploys 100 remote recording units and can be configured for TEM, induced polarization, MT, or CSAMT surveys.

In the 1990s, Electromagnetic Imaging Technology, under sponsorship from Western Mining, developed the SmartEM system which records and performs signal processing on the full TEM waveform before stacking which led to an order of magnitude improvement in noise suppression in areas of high man-made electromagnetic noise. Similar capabilities have also been introduced by Zonge Engineering and Research in their GDP32II receiver.

Airborne EM methods. A major change from the pre-1990 systems has been the use of low transmitter frequencies (25 or 30 Hz) instead of the higher frequency of 125 Hz common in North American surveys of the 1980s. The lower frequency has created opportunity for the use of airborne EM (AEM) over large parts of Australia, southern Africa, and South America where conductive cover screens basement conductors from the older AEM systems. Another change from the pre-1990 systems has been the transition from using half-sine wave transmitters to square-wave transmitters.

In the past few years, helicopter time-domain systems have come of age and taken over from helicopter frequency-domain and fixed-wing time-domain systems as the most common airborne surveys for mineral exploration. Steady improvements in signal processing and increasing transmitter dipole moments have proven that such systems are capable of conductor detection to depths of several hundred meters in ideal conditions, coupled with very high spatial resolution. In addition, many such systems allow robust and reliable conductivity mapping to aid geologic interpretation. Multiple systems of at least seven different hardware designs, namely Newtem (USA); Hoistem (Australia); VTEM, Aerotem, THEM (all Canada); Explorhem (South Africa); and Impuls A-2 (Russia) are all finding routine use at the time of writing, and other systems are under active development. With the good dip sensitivity and accurate GPS positioning of concentric-loop systems in use, drill holes are now being located using airborne electromagnetic data alone, without the need for expensive ground follow-up.

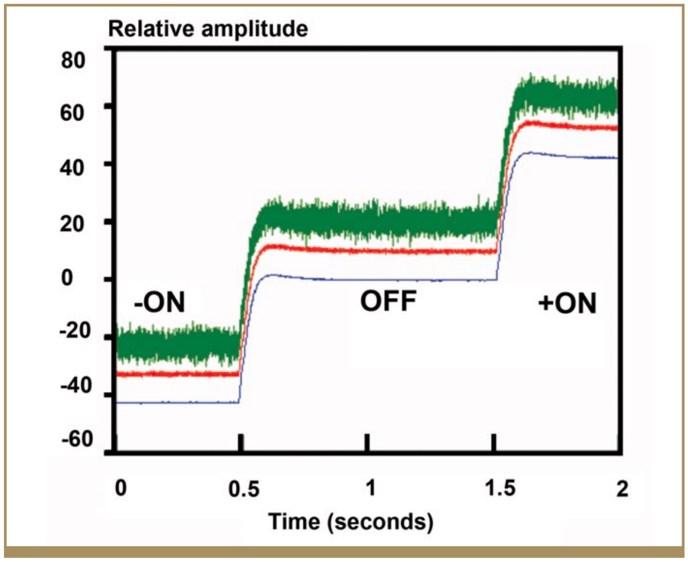

Figure 1. *Several half-periods of observed voltage data stacked in a SmartEM receiver, plotted as 2500 samples over a 2-s half-period. The transmitter is off for the central half of the plot. The Fluxgate (green, offset +20) and HTS (red, offset +10) data are vertically shifted from the LTS (blue) response for ease of visualization.*

As with every other branch of technology, the evolving speed of the silicon chip and of streaming data to hard disk has revolutionized data collection: the systems of today can record full-waveform data prior to stacking, which allows effective removal of magnetic noise spikes (due to spherics, strongest in tropical zones and during summer), thus expanding the geographical and seasonal opportunities for surveys. Some effort has been expended in increasing the bandwidth of AEM systems by recording the secondary magnetic field, rather than the time derivative conventionally measured as the output from an inductive coil receiver.

The use of fast, approximate algorithms and stitched 1D inversions to transform either TEM or FEM data into conductivity-depth images (CDIs) has proved invaluable in the interpretation of AEM data. At least six approaches for time-domain data have been published and a further three or more algorithms are in use for helicopter frequency-domain EM. Conductivity depth images provide not only a visual separation between surficial and deep conductors, but they also provide a tool for rapid estimation of layer thicknesses. This presentation method has transformed AEM methods from a "bump-hunting" tool used at the prospect scale, to a mapping tool.

The large number of time windows in airborne TEM (typically 20 per component), and the high degree of correlation between channels, make data-compression schemes attractive. Green (1998) showed how principal component methods

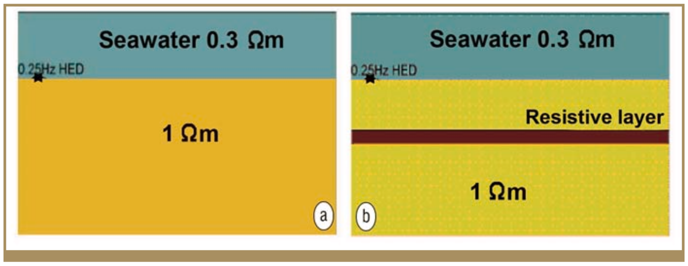

Figure 2. *(a) The two-layer case (sea and subsea). (b) The four-layer case incorporating a resistive layer situated 1000 m below the seafloor, having a thickness of 100 m and a resistivity of 100 ohm-m. The sea depth is 1 km and the transmitter frequency is 0.25 Hz.*

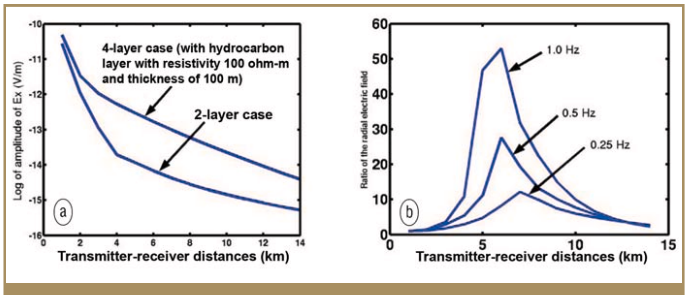

Figure 3. *(a) Calculated radial electric field obtained with an inline array over the two models shown in figure 1; (b) the normalized response for variable frequencies. Sea depth is 1 km.*

(previously developed for processing radiometric and satellite images) give enhanced differentiation of conductive units.

Marine-controlled source electromagnetic methods. Over the last two decades various university researchers (Scripps, University of Toronto, Cambridge, and later Southampton University) have used both natural electromagnetic fields and active EM sources to infer the conductivity structure beneath the sea floor. Measurements have been carried out both in time and frequency domain and all types of source configurations were proposed and used, from horizontal to vertical electric dipoles (HED and VED) to horizontal and vertical magnetic dipoles (HMD and VMD). An exhaustive and still valid treatment of these controlled source EM imaging (CSEM) techniques can be found in Chave et al. (1991).

One advantage of subsea measurements is that the highly conductive sea (between 2.5 S/m near the poles and 5 S/m in the tropics) acts as a low-pass filter for fluctuating EM fields generated above it either in the ionosphere or magnetosphere. At frequencies as low as 1 Hz, a few hundred meters of water will practically eliminate the effect of above-water EM sources including man-made or cultural noise. Repeated measurements of the seafloor electric field have determined that the natural and man-made background noise, at frequencies around 1 Hz, is of the order of 1 pV/m. This background noise includes the effects of continuous sea motion in the earth's magnetic field, surface gravity waves, microseisms, swell and wind waves. Repeated measurements have also shown that, despite all the above noise sources, weak electromagnetic fields that propagate in the underlying sediments from a sea-bottom artificial source are measurable at large transmitter-receiver separations of the order of many kilometers.

Recently the marine CSEM technique was applied commercially by Statoil to the problem of detecting the presence of hydrocarbon-filled layers in deepwater areas (Eidesmo et al., 2002). The CSEM technique uses a mobile horizontal electric dipole (HED) source and an array of electric, plus on occasion magnetic, dipole field receivers located on the seafloor. The HED source emits a low frequency electromagnetic signal (usually from a few tenths to a few Hz) that diffuses outward through both sea water and through the subsea formations. Due to the lower conductivity of subsea formations (less than 1 S/m), the diffusion rate of EM signals through the seafloor will be higher than that directly through the sea. As a result, at a suitable horizontal range, the electric field measured at the seafloor by a receiving electric dipole can be dominated by the response from the subsea formations. The measurements of both the amplitude and phase of the receiving signals can then in principle be used to determine the subsea geology, especially if it contains a higher resistivity hydrocarbon filled layer.

The CSEM technique is used in two modes: inline and broadside. In the inline mode, the transmitter and receiver dipoles are collinear while in the broadside mode they are parallel. Each electrode configuration has its own advantages and disadvantages.

On the theoretical side the EM response over a layered earth can be decomposed into two modes: transverse electric (TE) and transverse magnetic (TM). In contrast with MT, where the transverse modes are calculated with respect to the strike of the target, in the 1D layered earth case the transverse modes are calculated with respect to the vertical Z axis.

The TM mode, also called the galvanic mode, is the predominant mode in the detection of resistive targets. The reason for this is that the vertical component of the electric field undergoes drastic changes in going from a conductive to a resistive layer and vice-versa. In crossing the boundary between two media the total current is preserved and as such, if the conductivity decreases the electric field increases proportionally to keep the current density constant. This mode responds better to the inline array. In the TE mode, also called the inductive mode, currents flow in horizontal planes and we have inductive coupling between various layers. This mode responds better to the broadside array.

Most published work to date has dealt with simple 1D models investigating the diffusion of EM signals through either a simple two-layer structure (Chave, 1982), representing the sea and the subsea, or a four-layer structure which incorporates a thin, higher resistivity hydrocarbon-filled layer (Figure 2). Following Eidesmo et al. (2002), we present in Figure 3a the calculated response for the inline array for the two models shown in Figure 2, and in Figure 3b we present the normalized response (i.e., the four-layer response divided by the two-layer response for different frequencies). The relative increase in signal strength in the presence of a resistive layer is obvious and becomes more prominent with larger sea depths. Noteworthy is also the presence of the air wave (i.e., the signal that travels from the transmitter to the sea surface, then along the sea-air boundary and then back to the seafloor receivers) which manifests, in this case, as a break in slope around 3.5 km transmitter-receiver separation.

Controlled-source EM can in principle discriminate between water-saturated reservoirs (low resistivity) and hydrocarbon-saturated reservoirs (high resistivity), hence decreasing the risk of drilling dry holes. In addition to detection of resistive layers, CSEM, under favorable conditions, can also identify its edge(s) and, hence, can estimate the lateral extent of hydrocarbons within the reservoirs.

Unfortunately, very few case histories (e.g., offshore Angola, Troll Field on the Norwegian shelf) have been published as of this writing to properly evaluate the technique. There is, however, increased activity in this area. Besides Statoil (emgs—ElectroMagnetic GeoServices), heavy investments in developing marine CSEM were made by ExxonMobil, University of Southampton (OHM—Offshore Hydrocarbon Mapping), and recently Schlumberger acquired AOA Geomarine Operations. It is also worth mentioning that a Morgan Stanley report dated 30 August 2004 estimates that, in a few years, CSEM expenditures will reach 25% of the current spending on offshore seismic.

Borehole EM methods. Borehole geophysics for mineral applications has been primarily driven by the need to map ore-waste cut-off boundaries. Borehole EM for mineral exploration purposes has seen some advance in the last decades. Three-component borehole probes are now standard, and fluxgates allow B as well as dB/dt field mapping which aid excellent conductor detection by systems using off-time waveforms. Interpretation using filament-based or plate-in-air algorithms remains the norm, despite advances in 3D EM modeling. Some advances in software that allow models of multiple inhomogeneous and curved conductors in free space remain however proprietary.

EM modeling and inversion. The last decades have been one of large advances in both EM modeling and EM inversion. Despite major advances in 2D and 3D EM modeling, imaging of EM data using 2D or 3D algorithms remains firmly in research institutions, and most 3D modeling software is still difficult to use, with many (often undocumented) pitfalls and limitations (Smith and Paine, 1997). An excellent review of 3D EM modeling issues can be found in the *Proceedings of the International Symposium on 3D Electromagnetics* (1999). A complete description of significant advances made in this area is beyond the scope of this review.

Most techniques work reasonably well for moderate conductivity contrasts; low and high conductivity contrasts are not as well imaged. However, significant progress has been made in improving the high contrast cases using edge element formulations. For mineral-type targets where conductivity contrasts are very high, inductive-limit and resistive-limit modeling represent an alternative approximation approach, as does the multiple, inhomogeneous, curved plate model recently developed by Lamontagne, Walker, and others.

MT methods have seen some of the major advances in EM modeling and inversion, leading to similar developments in the controlled source area. Parallel computing resources are now used to fully tackle a 3D inverse problem with a high degree of discretization. A number of techniques, developed for inverting cross-well FEM data are now applied to mining exploration problems. A comprehensive treatment and reference list can be found in Nabighian and Asten (2002).

Suggested reading. "Controlled electromagnetic sources for measuring electrical conductivity beneath the oceans 1. Forward problem and model study" by Chave and Cox (*Journal of Geophysical Research*, 1982). "Electrical exploration methods for the seafloor" by Chave et al. (in *Electromagnetic Methods in Applied Geophysics*, SEG, 1982). "Sea Bed Logging (SBL), a new method for remote and direct identification of hydrocarbon-filled layers in deepwater areas" by Eidesmo et al. (*First Break*, 2002). "Mapping of induced polarization using natural fields" by Gasperikova and Morrison (GEOPHYSICS, 2001). "The use of multivariate statistical techniques for the analysis and display of AEM data" by Green (*Exploration Geophysics*, 1998). "Metalliferous mining geophysics—State of the art in the last decade of the 20th century and the beginning of the new millennium" by Nabighian and Asten (GEOPHYSICS, 2002). *Three-Dimensional Electromagnetics* (edited by Oristaglio and Spies, SEG, 1999). "MIMDAS—a new direction in geophysics" by Sheard (ASEG 1998 *Conference and Exhibition Abstracts*). "3D TEM modeling—a user's view" by Smith and Paine (in *Three-Dimensional Electromagnetics*). @75

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James Macnae *has made major contributions in electromagnetic methods in interpretation methodology, mineral exploration, sensors and instrumentation, robotic aircraft, unexploded ordnance detection, salinity mapping, and crustal conductivity sounding. Macnae received the Best Paper in* GEOPHYSICS *award in 1984, and the UTEM system it described has been responsible for the discovery of numerous mineral deposits. He has also received two best paper awards from the Australian SEG. Macnae's research in the past 10 years has resulted in software (e.g., EMFlow, BField) and hardware (e.g., low temperature Squid sensors, inductive E surveys, EM gradiometers) developments that have been commercialized.*

Marsh buggy on survey in SW Louisiana, 1962 (Photo courtesy Texas Instruments).