Airborne Frequency-Domain EM—Review and Preview

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ABSTRACT

Frequency-domain electromagnetic (FDEM) methods were responsible for the first airborne electromagnetic (AEM) discoveries, over forty years ago. Despite early competition from time-domain technologies, FDEM and particularly helicopter electromagnetics (HEM) have flourished and diversified over the years, and are among the principal tools of mining exploration. As sensor and interpretation technologies have matured, applications have become increasingly quantitative, especially in engineering and environmental tasks. Refinements in the FDEM method developed for these applications are now being applied to mineral exploration. Calibration accuracy and stability has emerged as an important factor in the quality of interpretation of the data from these quantitative surveys. Difficult exploration problems such as detection of subtle features which are currently inaccessible due to insufficient system accuracy and resolution are becoming tractable as the technology continues to improve. Concerted effort by explorationists and instrumentation/interpretation specialists will be critical to the development of these new applications. Technical improvements over the next ten years will likely include further integration of system hardware and software, the introduction of systems with wider spectral ranges and densities, enhanced calibration capabilities, reduction of system noise and drift, and better tracking of sensor orientation.

INTRODUCTION

Background

Frequency-Domain Electromagnetics (FDEM) encompasses a broad range of geophysical instrumentation sharing one common factor: they measure the Earth's electromagnetic response at one or more discrete frequencies. This range includes passive and controlled-source methods, techniques which measure secondary or total field responses, tilt angle and ellipticity, and one or two phase components. For the purposes of this paper, only the subset of FDEM methods comprising airborne techniques utilizing local controlled sources will be addressed. Methods such as VLF-EM, which derives primary field excitations from low-frequency radio signals, natural-field techniques, and the powerline harmonic system developed by the USGS (Labson, 1987) will not be included.

History: 1946–1987

The many excellent review papers published over the years (e.g., Collett, 1986, Palacky and West, 1991, Barringer, 1987, Becker *et al.*, 1987, Paterson, 1971, 1973, Pemberton, 1962, Ward, 1966, 1970) have thoroughly explored the development and successes of airborne EM methods from their earliest days and will not be recapitulated here. It is, however, interesting to observe the general pattern of development of the technology and applications. During the first twelve or thirteen years of airborne EM surveying, all systems operated at one or more fixed frequencies, which was natural given the electronic technologies available at the time. Due to difficulties in stabilizing the receiver bird location with respect to the continuously transmitted primary field, some systems measured amplitude differences at two frequencies, while others operated in the *quadrature* mode, that is, only the component of the earth's response which was out-of-phase with the transmitted signal was measured. A amplitude-difference survey, conducted with the INCO Anson system, was credited with the 1954 Heath Steele discovery in New Brunswick (Collet, 1986). This discovery, the first by an airborne EM system, led to a rapid proliferation of systems in use that has continued to the present time.

The advent of transient methods in the early 1960s did not eclipse FDEM technology. Instead, the application of frequency-domain methods gradually shifted to tasks for which they are better-suited, particularly contouring with helicopter platforms, high-resolution geological mapping and quantitative measurement of geological or engineering parameters. The ability of FDEM systems to operate over a wide spectral range, and particularly their ability to acquire data at relatively high frequencies, facilitated this transition. This proved to be extremely useful during (and indeed, was partially driven by) the gold boom of the mid-to-late 1980s, with its emphasis on detailed mapping of relatively resistive geological structures. Transient technology development continued to be focused on the detection of deep, highly conductive orebodies, although electronic and interpretational improvements in this field did

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lead to the construction of conductivity maps and related products, starting in the late 1970s or early 80s (Palacky, 1981). Another trend visible in the late 1980s was the move to digital data acquisition and real-time digital signal processing. This trend had an impact on both FDEM and transient technology which continued to build through the following decade.

PROGRESS DURING THE PERIOD 1987–1997

FDEM overview: 1987–1997

The decade 1987–1997 was a period of refinement and specialization for FDEM methods, with a number of innovations occurring in instrumentation, processing and applications. The most visible changes were that a variety of new instrumentation was developed or brought into production, while a few systems, such as Tridem® and Sweepem®, dropped out of use or development.

Instrumentation

FDEM systems in use today or within the last ten years include a variety of transmitter-receiver geometries, all of which fall into the *Rigid boom* EM category. Rigid boom technology, which is characterized by transmitter and receiver antennas separated and supported by a more or less rigid structure, includes Helicopter EM and Wingtip systems. A second category, *Fixed-wing towed-bird* systems, does not include any operational FDEM systems, although all commercial time-domain systems use this geometry.

Traditional or *narrowband* FDEM systems transmit sinusoidal signals at one or more frequencies and use analog or digital phase detection to extract components of the received signal which are in-phase and out-of-phase with the transmitted waveform. Phase-locked loops and other narrowband filtering devices are used to minimize the signal bandwidth and reduce output noise levels. *Wideband* approaches, which have been incorporated in some airborne systems, utilize non-sinusoidal transmitter waveforms. They Fourier-transform the received signal time series, filter and calibrate some or all of the transformed signal's components, and output these as phase components at discrete frequencies. A rigid transmitter-receiver geometry is required for such systems because changes in the received field due to variations in this geometry would be indistinguishable from anomalies in the measured secondary field.

Helicopter rigid-boom electromagnetic systems constitute by far the largest number of FDEM installations, with approximately 22 systems operational worldwide. The great majority of these systems utilize resonant-mode coils as their transmitting and receiving antennas, although wideband technology has begun to make inroads over the last five years. Most rigid-boom systems actually utilize three coils for a given antenna configuration: transmitter, receiver and *bucking coil*. The function of the bucking coil is to null out of the primary-field signal being picked up by the receiver coil, thereby reducing dynamic range requirements in the signal processing and data acquisition electronics. Antenna configurations in common use include:

- the horizontal coplanar mode, in which the normal vectors of the coils are vertical;
- the vertical coaxial mode, in which the normal vectors of the coils are horizontal and aligned with the flight direction;
- the vertical coplanar mode, in which the normal vectors of the coils are horizontal and perpendicular to the flight direction;

A fourth configuration in which the transmitter and receiver axes are at right angles, which is known as the null-coupled mode, is rarely used in operational systems at the present time.

Wingtip systems, in which the transmitter and receiver antennas reside in pods or similar structures mounted near the wingtips of fixed-wing aircraft, are not in wide use at the present time. The Geological Survey of Finland is the only known operator of such a system, which utilizes a two-frequency vertical-coplanar configuration.

Fore-and-aft systems, in which the transmitters and receivers are mounted at the nose and tail of a fixed-wing aircraft, appear to have fallen completely out of favour.

Processing

EM datasets, particularly those acquired for mineral exploration purposes, were typically presented as profile maps, stacked profiles, and single-frequency resistivity maps. Very few changes occurred in these established procedures and products over the 1987–1997 period.

One data presentation which did become widely available during this period was the *depth pseudosection*. A variety of techniques were used to generate these (e.g., Sengpiel, 1986), all of which sought to render an approximate one-dimensional (1D) mapping of the earth's conductivity variation with depth without performing a multifrequency inversion of the data. Under good circumstances, such pseudosections permit a certain amount of qualitative interpretation of the EM dataset to be performed. They all suffer, however, from substantial underutilization of the information content of the EM and altimeter datasets, leading to poor depth resolution.

Layered-earth inversion has become a routine processing task for certain quantitative applications such as bathymetry and sea ice thickness mapping (Holladay *et al.*, 1990), Real-time, quantitative inversion for sea ice thickness was demonstrated for the first time in 1991 (Rossiter and Holladay, 1994). Real-time, multifrequency inversion for sea ice thickness and conductivity was first demonstrated in 1995 (Holladay *et al.*, 1995). Inversion was also applied to a variety of other mapping problems, particularly the mapping of overburden or of specific (usually shallow) layers within thick overburden (Hogg and Boustead, 1990, Gamey *et al.*, 1997).

Applications

Over the last ten years, there has been a trend in the specification of airborne EM surveys toward the addition of a gamma-ray spectrometry package and away from use of the VLF option. This stems from the increased levels of activity in areas (arid and tropical terrains) where radiometric techniques have proven useful for the mapping of geology and alteration zones. A contributing factor has been the poor VLF signal level in many areas where radiometrics have proven useful.

The application of HEM became broader, in both the geographic sense and in terms of the information and/or target sought, during this period. Since the early 1980s, HEM has been used increasingly in parts

Figure 1: *The INCO quadrature system, mounted on an Anson, circa 1954. The transmitter antenna is mounted directly on the wooden skin of the aircraft, while a towed bird (visible below the port engine) housed the receiver coils.*

of the world that were rarely, if ever, surveyed with HEM. For example, surveys were conducted in the Middle East, Turkey, southeast Asia, the central Asian states, West and Central Africa, and Australia as western exploration companies started exploration programs in these areas.

Accompanying geographic diversification was an increase in the range of applications of HEM, brought about by specialized design and by the availability of robust EM inversion software.

Light weight or high altitude systems were developed to permit for surveying in rugged areas of high altitudes (over 4,000 m) with standard helicopters. Another factor in the introduction of such systems was the desire to decrease field costs through the use of less expensive helicopters, often having limited payload capacity. Specialized EM systems were also built to conduct engineering or geotechnical applications such as sea-ice measurements (Holladay *et al.,* 1990.) These systems are often smaller and lighter than conventional systems. They typically have a shorter receiver to transmitter separation, incorporate fewer discrete frequencies or are wideband systems, and utilize higher operating frequencies.

At the other end of the size and frequency scale, larger systems were developed to conduct bathymetry work to sense through up to 50 m of

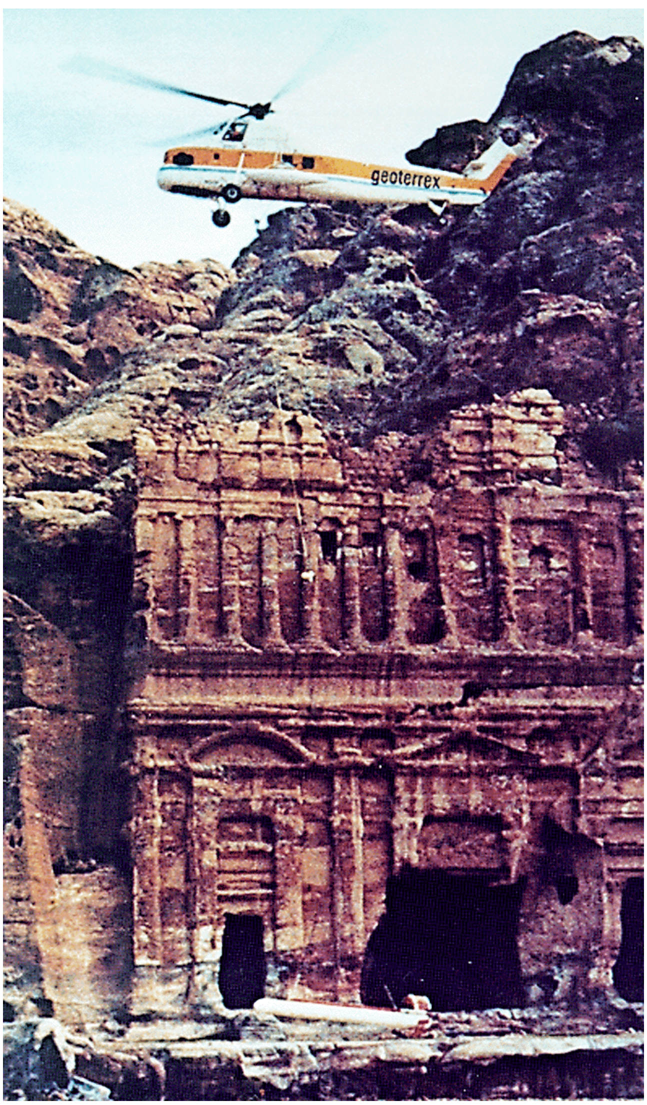

Figure 2: *Helicopter Electromagnetic systems.* ***Left:*** *Geonics EM-33, circa 1980, courtesy of Geoterrex;* ***Above:*** *Aerodat 5-frequency HEM, circa 1996. While the general appearance of HEM equipment has changed little since their introduction in the late 1960s, they have become much more sophisticated in terms of their noise, drift and calibration stability over the last ten years.*

Figure 3: *Geophysical Survey of Finland dual-frequency Twin Otter system. Narrowband transmitter and receiver antennas are mounted at the aircraft's wingtips.*

sea water (Holladay *et al.,* 1994). These systems have a larger transmitter moment, utilize lower operating frequencies and operate over a wider *spectral range* (greater than 730) than other HEM systems. So far these larger systems have not been used for other applications.

Traditional applications of HEM continue to be important. The principal factors for selection of HEM over fixed-wing systems still include rugged topography in the survey area, exploration for highly conductive targets, and high survey resolution. Resolution of HEM systems is typically much higher than for fixed-wing systems due to the slower flying speed and the smaller sensor-to-source distance.

A prime example of an exploration play ideally suited to HEM surveying was seen in 1995 when nine or more HEM systems were engaged in surveys in the vicinity of a large nickel-copper-cobalt discovery near Voisey's Bay, Labrador, Canada. A combination of rugged topography, the large size and very high conductance of the sulphides led to the exclusive use of frequency domain systems for airborne EM work in the area.

In the Cordillera and in other rugged areas, HEM is generally the most suitable airborne EM technique, as the helicopter's contouring capability can be used to keep the EM sensors close to the ground. A large number of HEM surveys were conducted during the early 1990s in the South American Cordillera, in particular.

Exploration for diamondiferous kimberlites, which generated a large number of surveys during the late 1980s and early 1990s in the Northwest Territories of Canada, also favours HEM technology due to its excellent resolution of these relatively small and low conductance targets.

In other cases, it is the large conductance (over 200 S) of a survey target which dictates that frequency domain HEM be used. Magmatic sulphides associated with ultramafic rocks are typically extremely conductive. Such sulphide bodies generally display time constants longer than can be resolved by typical airborne time domain systems if they are of economic size.

Exploration for moderate to good conductive targets such as volcanogenic massive sulphides (between 10S and 200S) in areas of gentle topography are suitable for both fixed-wing and helicopter surveying. In this area of overlap, a balance must be struck between resolution (favours helicopter), depth of investigation (favours fixed-wing), availability (favours helicopter), and cost (favours fixed-wing).

The period between 1987 and 1997 also witnessed the increasing use of HEM applied to the indirect detection of economic mineralisation. Such indirect detection methods include the mapping of alteration zones, searching for the host of the mineralisation, or seeking the weathering signature of the economic mineralisation. For example, when using HEM for gold exploration in Canada, the rationale was to use electromagnetics to detect local shear and fracture zones which sometimes host gold mineralisation. Interest in using airborne geophysics to locate porphyry and hydrothermal gold deposits also grew during the 1987 to 1997 period as interest in gold exploration grew. During this timeframe, a number of papers on HEM applications in the search for such deposit types were published (e.g., Johnson *et al.*, 1985). In all of these cases, EM was employed to search for alteration or for the host of the gold deposits rather than attempting direct detection of the ore body. This requires an increased knowledge of local geology and the mineralizing process to understand the different geophysical signatures.

Another example of this approach is the use of HEM to detect the weathered and conductive layer which caps kimberlitic rocks. The small size and conductance of the targets virtually dictates that profile-based EM interpretation be used for analysis of reconnaissance survey data. Line spacings narrow enough to adequately sample these features for grid-based interpretation are very useful for detailed or follow-up surveys of specific targets, often selected on the basis of earlier regional surveys.

Finally, as an example of extremely indirect detection of mineralisation, HEM has been used to detect and delineate buried paleochannels which may contain placer mineralisation. Such surveys, particularly for small features, benefit from the high resolution, geometrical diversity and spectral range of HEM.

PRESENT STATE OF THE ART

Applications

Frequency-Domain EM methods, and particularly HEM, are presently employed in a wide variety of measurement tasks. These will undoubtedly continue to account for most FDEM survey work during the next decade, and include:

Standard HEM survey tasks:

- the search for highly conductive to moderately conductive sulphides, moderately conductive shear zones for gold
- work in high or rugged terrains inaccessible to fixed-wing systems
- tightly controlled contour flying

High resolution tasks:

- searching for multiple conductors and small targets
- kimberlites
- hydrothermal systems
- surveying areas where ground geophysics (including access, line cutting etc.) are many times more expensive and much slower
- paleochannel exploration where detectable property contrasts exist
- mapping of alteration zones

Geotechnical tasks:

- acid mine drainage
- bathymetric and sea-ice thickness measurements
- geotechnical surveying of large and/or extremely hazardous areas for disturbed soil (pits and trenches) and for direct detection of buried objects and groundwater contamination plumes

Most of these applications are well-established, while few if any may be classed as truly new or emergent. However, technological improvements in hardware, processing techniques and interpretational software may well enhance certain AEM capabilities to the point at which subtle but geologically important features can be resolved on a routine basis.

Methodology and specifications

Survey methodologies for the majority of HEM systems and applications have not changed significantly over the last decade. More background readings are currently obtained to provide better estimates of system drift, and in more conductive environments, these readings are made at higher altitudes. The effort of setting up navigational transponders has essentially disappeared now that GPS coverage is complete: magnetic base stations now routinely incorporate a GPS base station.

Among specialized systems, there are now "lighter weight" systems which do not require an operator in the helicopter. These systems are more or less automated and the pilot is responsible for a minor amount of equipment operation during the flight. Obviously, a high degree of reliability must be incorporated into the automation of these systems to minimize collection of unacceptable data.

Most FDEM survey specifications have not changed significantly over the decade. Client attention is often more focused on flight path accuracy, the contouring ability of helicopter pilots, and the pilot's ability to control the EM bird while in flight, than on the noise characteristics of EM systems. While the flight path and the pilot's skill are important components of a good survey, it can be argued that there is a lack of knowledge by many users of AEM which makes it difficult for them to distinguish between acceptable and unacceptable data. Confusion also exists in the definition of noise, since the normalised units of measurement typically used are dependent on coil separations which vary between different HEM operators. The sheer variety of filter types, corner frequencies, and plotting scales in use further complicate the picture. A complete specification of acceptable noise levels should thus include coil separation and a formula for transforming between different coil separtions, the noise measure being used (e.g., peak, peak-peak, rms), the anti-alias filter corner frequency, and the fraction of all measurements permitted to exceed the noise specification during a given time interval. It is usually difficult to measure noise levels while the bird is at survey height, since geological responses at this altitude form some or most of the measured variation. Noise levels are therefore normally specified for a system at background altitude, and should remain within acceptable limits over a reasonable range of bird pitch and roll variation.

Most HEM contractors now offer in-field data verification and processing. This allows for assessment of data integrity and quality and, depending on the sophistication of the in-field system and the knowledge of the field geophysicist, apparent resistivity maps can be generated along with magnetic intensity contours, EM profiles, and other products.

Hardware

There are at present two technologies in use for FDEM measurements, known as narrowband and wideband EM. These terms were defined in "Instrumentation" on page 506, but merit a more complete discussion.

A distinction should be made between the terms relating to *spectral range* and those related to the mode of data acquisition. Most conventional FDEM systems yield measurements of the earth's EM response over a wide spectral range, yet acquire their data in the narrowband mode, i.e., one frequency per coil pair. The spectral range of HEM systems may be represented in many ways, but one useful measure is the ratio of the system's highest and lowest frequencies. The ratio for most HEM systems used for exploration purposes fall into the range of 40 to 150. The ratio value for the TIBS™ bathymetric system is 730. A very simple measure of spectral range for an airborne transient system is the ratio of the system's longest delay time window to its shortest. Using this measure, spectral range ratios ranging from 3 to 60 have been estimated from published case histories. Note that this definition fails to take into account either the inherent strengths and limitations of various transient system waveforms in terms of their transmitted power spectra or the information content of their on-time channel(s).

The terms wideband and narrowband relate primarily to the style of data acquisition. As mentioned in"Instrumentation" on page 506, narrowband is used to used to denote transmission and acquisition of a single frequency per coil pair at a given time, while wideband denotes transmission and acquisition of multiple frequencies simultaneously using a single coil pair. Wideband measurements thus utilize time-domain acquisition but may present their results as either time-domain or frequency-domain responses.

It should be noted that there are ground EM systems which sweep through a range of frequencies, one frequency at a time. Such acquisition would be considered to be narrowband according to the definitions above, although the resulting dataset might be very similar to that obtained using a wideband system generating frequency-domain data.

Narrowband EM typically utilizes resonant transmitters and receivers to concentrate the transmitted energy in narrow spectral bands and to minimize the noise bandwidth of the received signal. Resonant transmitters have the advantage of requiring relatively simple, low-power

Figure 4: *HEM sensor size often depends strongly on the application. Sea ice measurement bird (top), TIBS™ bathymetry bird (middle), and standard 5-frequency bird (bottom).*

driver electronics, since most of the energy flowing in the transmitter circuit cycles from magnetic storage in the transmitter coil itself to charge accumulation in the series resonating capacitors and back again. Most of the complexity which does arise in such driver electronics relates to overload protection, dipole moment stabilization and frequency control. Resonant transmitters can be highly efficient in that, when suitably designed, they transmit almost all of their output in a narrow band about the resonant frequency. Similarly, resonant-mode receivers typically utilize a parallel-resonant circuit in which the inductor is the receiver coil and the capacitance is built up using highly stable capacitors. Resonance enhances the frequency selectivity and the signal/noise ratio of the entire receiver system by band-limiting the incoming signal, and permits the use of relatively simple preamplifiers. Resonant-mode systems have two significant drawbacks: the first is that their transmitters' and receivers' resonant frequencies typically drift slightly with temperature, which leads to temperature-related drift in the output data. The second is that a separate transmitter-receiver coil set is required for each frequency. Since each coil set has an intrinsic weight (which tends to be higher at low frequencies) and requires support within the bird, adding frequencies to an EM sensor bird increases its overall weight and complexity. Taking these factors into account, it appears that five or perhaps six frequencies represent the practical upper limit for resonant-mode systems.

The use of wideband technology in airborne EM systems eliminates many of the difficulties encountered in resonant systems, although certain common problems remain and a few new ones unique to wideband systems arise. The principal advantages of wideband over resonant technology are that properly designed wideband systems display low baseline drift relative to comparable resonant systems and can operate at many frequencies using a single coil pair. This reduces sensor weight considerably, particularly on a per-frequency basis. It also facilitates operation at software-controlled frequencies. One difficulty which has been faced during the development of wideband systems is that crosstalk between nominally orthogonal coil orientations operating at similar frequencies is more difficult to control, since the wideband receiver coils themselves provide less band-limiting at the front end. Considerable effort has also been required to devise suitable digital signal processing (DSP) software to perform the necessary filtering and phase analysis in wideband systems. The electronic and computing aspects of wideband EM development have been facilitated by the rapid progress in commercially available electronic components over the last decade.

A third class of FDEM systems exists in which the transmitter is wideband and the receivers are narrowband, or vice-versa. These systems do obtain some of the benefits of each of the basic technologies, but also inherit some of their disadvantages. Consider, for example, a wideband transmitter operated with a set of narrowband receivers. The transmitter can operate at a tightly-controlled and constant base frequency, but does not concentrate all of its transmitted energy on the few harmonics of the base frequency that are being measured by one or two narrowband receivers. Thus, its wideband transmission capabilities are not being fully utilized. The narrowband receivers also display drift higher than that which would be encountered in a properly-designed wideband system, although the immunity of the system to line noise such as power line harmonics or VLF transmissions will be improved by the receiver tuning, unless the operating frequencies were poorly chosen. Also, the physical complexities of mounting multiple receiver coils for different frequencies limits the number of frequencies at which the system can operate, while the weight of the support structure and of the coils themselves adds to the overall bird weight. Finally, a narrowband receiver's operating frequency cannot be changed under software control without a great deal of electronic complexity, which limits the flexibility of the system.

As another example, consider a pair of efficient, tuned narrowband transmitters operating with a single wideband receiver coil. In this case, the receiver coil is lightweight and relatively stable with respect to temperature, but the transmitter frequencies will still vary with temperature, generating moderate drift in the measured response. The noise immunity of the receiver can be no better than any other wideband system utilizing similar signal processing. Multiple transmitter coils, with their supporting structures, add substantially to the bird's weight. As with the previous example, resonant transmitters cannot change frequency under software control without using electrical switching to change the resonating capacitor values.

At the present time, an estimated 80% of operational FDEM systems are narrowband. Approximately 12% are wideband, while the remaining 8% are hybrids with wideband transmitters and narrowband receivers. These estimates are based on the best available information, and may be in error by 5% or more. Most of the true wideband systems are small, lightweight birds which were developed to address specific engineering or environmental applications, with the rest developed particularly for mineral exploration. The inherent physical simplicity and resulting light weights of wideband HEM systems make them particularly well-suited to surveying at high elevations, where helicopter payloads are limited.

One trend observed during the last ten years, which seems likely to continue, is the incorporation of auxiliary instruments into HEM birds. These instruments, such as attitude sensors, altimeters, magnetometer sensors and GPS receivers are principally used to correct for error sources during quantitative data interpretation, mainly in engineering and environmental applications, and to provide higher-resolution magnetic field measurements. At the present timea severe bird swing and an conductive environment are required to generate significant artifacts. However, as 2-D and 3-D EM inverse modeling capabilities improve and joint inversion of multifrequency EM with other sensor data comes into use, a precise knowledge of bird orientation and altitude will become critical to accurate interpretation.

Data processing

Helicopter electromagnetic systems are usually flown with a magnetometer (or magnetic gradiometer), and often with gamma-ray spectrometer or VLF. The processing of the latter data streams and of positioning instrumentation data are treated elsewhere and will not be covered here.

Given the degree of specialisation and small size of the airborne market for software vendors (approximately ten companies conduct AEM surveys), it is hardly surprising that all of the commercial software packages which are presently available to process airborne data lack an electromagnetic data processing module. All of the major electromagnetic contractors have developed and support their own data processing software for electromagnetics.

Fundamental to HEM processing are noise rejection, drift correction and absolute calibration. Since all data are collected in digital form, a variety of digital filtering processes may be applied to remove noise, provided that features exist which distinguish noise from signal in frequency and/or amplitude characteristics.

Drift in electromagnetic data must be measured and removed before further processing is undertaken. Traditional methods of estimating drift using *background readings*, i.e., EM data collected at altitudes which are presumed to be high enough that the response of the ground is below measurable levels (or can at least be accurately predicted), have not changed significantly. Current quantitative survey methodology requires that background measurements be obtained more frequently than in the past, in order to measure and remove drift more accurately. In highly conductive terrains, this background reading must be obtained at approximately 400 metres terrain clearance. Under some climatic conditions, the process of background measurement, particularly at such high terrain clearances, introduces its own drift component arising from the temperature gradient with altitude. A balance must therefore be struck between drift arising from temperature and other changes normally occurring during the course of low-level survey flying and drift introduced during acquisition of background measurements.

Calibration accuracy in HEM data is becoming increasingly significant, particularly for engineering applications where quantitative interpretation is often critical. In mining exploration, the need for improved calibration was driven first by apparent resistivity maps becoming standard products and, more recently, by the increasing interest in geoelectric sections. Stable and accurately-known system calibration is achieved in large part by careful system design, complemented by suitable field methodology. It must be rigourously monitored during surveys to alert field and processing personnel to unexpected changes, which are typically caused by malfunctions or by damage to a system component. If proper procedures are followed, the traditional methods of phase and amplitude calibration by ferrite bar and internal/external Q coils can yield calibration accuracies as high as 1%. Newer methods can deliver much higher precisions on a real-time basis, but require specially-equipped birds.

Electromagnetic data are often presented in the form of offset profiles, usually with the co-axial and co-planar coils of similar frequency plotted together at a 1:4 scale to account for the different primary field strengths used in the normalisation. For the detection of conductors in a resistive terrain, this is still the most popular method of presenting EM data.

Another standard presentation is known as the *apparent resistivity* map. Apparent resistivity, which is a conceptually straightforward mapping of measured inphase and quadrature values into apparent halfspace resistivity and apparent sensor height, is calculated and presented on a frequency-by-frequency basis. While this process can be executed using a parametric inversion routine applied to each frequency being considered, it is typically performed through the use of a pair of two-dimensional lookup tables. Resistivity maps are complementary to profile maps in that they are not generally suitable for picking of bedrock conductors in resistive host rocks, but are instead helpful for discrimination of geological units under overburden and for more general mapping of laterally extensive features.

In the presence of near-surface magnetic or permeable sources, AEM can be used to make approximate apparent susceptibility measurements. Some work was published in the early 1980s regarding the calculation of volume percent of magnetite using observed negative inphase measurements (Fraser, 1981) but this method has not been heavily used owing to its limited exploration application and difficulties in removal of terrain clearance effects. Further papers have been presented in the last two years (Zhang and Oldenburg, 1995, Qian *et al.,* 1996) which demonstrate a new interest in this problem.

Occam inversion, which searches for the smoothest possible model consistent with the input data and subject to a given quality of fit criterion, appears to be a useful and robust alternative to conventional layered earth inversion. The method is especially well-suited to automated interpretation of large volumes of survey data over complex layered structures, in that minimal manual intervention is required during processing to extract the majority of the geoelectric information. However, like all quantitative inversion methods, Occam inversion requires properly leveled, accurately calibrated data inputs. Systematic errors due to calibration or drift errors may generate misfits larger than the fitting tolerance, causing convergence failure. Occam inversion can be used for 1D and higher-dimensional problems, but the paucity of fast forward models for 2-D and 3-D geometries, coupled with the compute-intensive nature of the Occam approach, means that only 1D analysis is currently practical for commercial applications.

The sensitivity to relatively minor inconsistencies in the data is one important reason for the relative rarity of such inversion products prepared for routine mineral exploration surveys. Only recently have EM systems appeared with low drift and stable, accurately known amplitude calibrations which are consistent from frequency to frequency. There are other reasons for the scarcity of routine multifrequency inversion, of course, particularly the importance of lateral variability in both surficial and bedrock geology in many geological settings. Subsurface lateral inhomogeneities which occur on a length scale shorter than a few times the EM system's altitude above the ground cannot be accurately modeled using 1D inversion routines. If an inverse model is prepared, it tends to show a relatively smooth variation of layer conductivities, with strong misfits where rapid lateral variation takes place.

Interpretation

Contractors usually supply their clients with a computer generated set of interpreted conductor parameters such as dip, depth, and conductance for discrete and identifiable EM conductors. These conductor parameters are interpreted by experienced interpreters, or via some automated routine which, for example, might search for local maxima in the co-axial responses, then obtain the conductor parameters from a lookup table. Symbolic representations and automated techniques are generally limited to steeply dipping thin sheet conductors.

The tried and true method of putting an experienced geophysicist on-site to monitor the survey for data quality and at the same time produce a preliminary interpretation is still widely used. Nowadays, such a geophysicist may utilize a portable computer with suitable software for calculating magnetic and radiometric grids and for grid filtering operations. A variety of EM modeling programs have been available for use with personal computers for some time now. At least two programs which calculate the response of a conducting plate are available at nominal cost, as is a model for a sphere in free space. Robust two dimensional modeling have recently become commercially available. Two dimensional EM inversions are also available, at least within certain industry-university cooperative groups or consortia. It is anticipated that two dimensional inversion software will be widely available in the near future.

Apparent resistivity maps are often used when HEM methods are applied to geological interpretation. These maps are in many respects much superior to the EM profiles for the interpretation of geology, since the use of an (apparent) physical parameter rather than a normalised measure of secondary magnetic field eliminates some geometrical (e.g., terrain clearance) effects. However, the elementary half space model which forms the basis for apparent resistivity inversion does not make full use of the information contained in different coil configurations, nor does it make effective use of multiple-frequency data, apart from the calculation of separate apparent resistivities at each frequency. More complicated resistivity inversion schemes which yield apparent two-dimensional geoelectric sections are an emerging approach toward making use of multiple frequencies and different geometries.

As the applications of HEM emcompass more indirect detection of economic mineralisation, an understanding of local geology, alteration history and possible target response or signatures becomes even more important. While forward and inverse modeling can provide a geoelectric model of the earth, it still does not interpret the various conductivities into alteration or mineralisation estimates.

THE FUTURE: WHAT WILL THE NEXT TEN YEARS BRING?

Change is one of the few constant factors in airborne geophysics. Instrumentation, computers and software, even the algorithms and paradigms used for geophysical interpretation are all evolving rapidly. Any attempt to forecast technological progress in this field, particularly over a span as long as ten years, is thus speculative. However, in looking back over the literature of the last forty years, the evolution of the geophysical principles and insights which underlie geophysical technology has been more gradual and perhaps predictable to some extent. If this pace continues into the next decade, present geophysical trends may provide at least a partial guide to future developments.

If one is willing to accept the validity of making forecasts based on recent history and current conditions, a number of likely directions for development emerge. To begin with, many of the changes observed in FDEM technology during the last ten years have been incremental in nature: noise and drift levels have been improved, calibration accuracy, the number of frequencies and system reliability have increased, but all by relatively small factors. It would appear that conventional FDEM, particularly narrowband HEM, has become a mature technology. The most significant changes anticipated over the next decade thus relate to:

- the continuing integration of hardware and digital signal processing software in both wideband and narrowband systems;
- the emergence of increasingly sophisticated wideband systems which may include the capability of supplying data in the frequency and time domains interchangeably or even simultaneously;
- a drive toward wider spectral ranges with a greater density of frequencies per decade (in wideband systems);
- continuing improvement of EM calibration precision and accuracy;
- more precise measurement of bird attitude during survey flying for exploration purposes; and
- further reduction of baseline drift.

Some of these ideas are explored in more detail in the following sections.

Increased integration of hardware and software in EM systems

The integration of hardware and software is well-advanced in fixed-wing transient systems. The same type of integration has been proceeding in FDEM technology over the last decade. For example, the availability of small, fast analog-to-digital converters and digital signal processors has led to the introduction of several generations of digital receivers, some small enough to be mounted within the HEM birds themselves, transmitting calibrated EM data to the data logging system in digital form. It is anticipated that this trend will continue, perhaps to the point where so-called *smart birds* will perform all EM acquisition and signal processing operations with only minimal external hardware and operator intervention. It is also likely that most HEM sensor platforms will incorporate one or more high-sensitivity magnetometers. As system weights, sizes and sensitivities continue to improve, it is even possible that remotely-piloted or unmanned autonomous aircraft will find a role in airborne EM data acquisition, at least in remote areas with low population densities. Payload limitations, low-level obstacle avoidance and liability concerns appear to be the most critical issues facing unmanned airborne EM surveying.

Further merging of TD and FD acquisition

New wideband systems, particularly rigid-geometry systems utilizing programmable waveforms with substantial transmitter-off periods, will gain the capability of operating in either the time domain, yielding a suite of off-time channels accompanied by one or more on-time channels, or in the frequency domain, generating multiple channels of inphase and quadrature response. The new HELITEM® tensor transient EM system, for example, possesses this capability. In fact, as acquisition software and computing capabilities become more sophisticated and powerful and data storage costs continue to decrease, it may become a common practice for contractors to offer response data in either domain. Technical impediments to such developments include the requirement for high transmitter moments, the requirement for a high degree of structural rigidity (which is difficult to reconcile with very large transmitter moments) and the need to buck out the effect of a powerful (presumably large-diameter) transmitter at the receiver coil.

Increased spectral range and spectral sampling density

Systems operating over wide spectral ranges and resolving many frequencies are also likely to become available, driven by the need for more detailed data for imaging and inversion processing. While it is unlikely that narrowband solutions, either of the traditional or step-frequency type, will be capable of supplying this capability, wideband technology is clearly headed in this direction. Technical challenges include the difficulty of integrating multiple wideband transmitter and receiver orientations while minimizing crosstalk and maximizing dynamic range, optimizing transmitter waveforms, and increased requirements for computing and data storage.

Interpretation

Electromagnetic interpretation methods may be expected to continue their growth toward quantitative 2-D and 3-D imaging and inversion, fueled by the availability of high-quality, accurately calibrated, multi-geometry data, by faster and more accurate forward modeling, and by steady increases in the speed and memory capacities of inexpensive desktop computers. The venerable apparent resistivity map will likely be augmented by apparent susceptibility maps also generated from the EM data. Layered-earth inversion, where appropriate, will become a standard data product. Inversion for the conductances and geometrical parameters of simple objects such as plates and spheres beneath conductive overburden and surrounded by conductive host rocks will also become routine. Robust inversion techniques may well become the norm for all classes of inversion, despite their (presently) high computational cost, because they make the best use of available data. A variety of *overburden stripping* techniques, in which the response of overburden is modeled and deconvolved from the EM signature of the target, may make the transition from experimental to operational use. Finally, and perhaps most speculatively, joint inversion of AEM with other airborne survey data may become a viable process.

Emerging applications

The introduction of new applications will be driven by economics and by the evolution of interpretation and hardware capabilities: improvements in these fields should make it possible to solve problems with AEM which are currently inaccessible. For example, detailed mapping of paleochannels in which contrasts between the channel fill and the surrounding medium are low is presently difficult: lower-drift systems with wider spectral range and density may improve discrimination of such features. Detection of more subtle grades or new types of alteration may also be facilitated by such improvements.

The future development or refinement of this type of application will require close cooperation between explorationists and contractors. The input of field geophysicists and geologists is critical, as they can identify specific classes of structures which might have a geoelectric expression and hence serve as a AEM target. Geophysicists associated with contractors who are fully aware of the current state of the art are well-positioned to judge whether a particular class of target structure can be detected in a practical manner. Solid in-house AEM modelling capabilities are also important aids to such an assessment. This approach to the development of new applications will probably be most successful in the search for indirect indicators of mineralisation. Substantial success has already been achieved in epithermal gold and diamond exploration, for example. As better system and interpretational capabilities are achieved, improvements in the detection and delineation of such subtle features should continue.

A variety of new applications in the engineering and environmental fields will probably arise, with high frequencies, high spectral sampling densities and tensor measurement geometries being key requirements for many near-surface applications. Relatively low survey volumes are an important obstacle to the continued development of these applications.

CONCLUSIONS

Frequency-domain airborne electromagnetic methods have played a significant role in mineral exploration since the early days of airborne geophysics. There is every reason to believe that these methods, particularly Helicopter Electromagnetics, will continue to serve as important tools for mineral exploration. Helicopter-borne systems achieve excellent lateral resolution through their low sensor altitudes and their ability to contour-survey in rugged terrain. Their ability to identify highly conductive targets makes them especially useful in the search for high-grade massive sulphides.

The diversity of HEM sensor sizes and applications is a strong indication of the relative maturity of the method. Another indication is the relatively slow rate of technological change observed, particularly for narrowband HEM systems. Two significant changes are the introduction of digital receivers and wideband data acquisition: these technologies may have a significant impact on the operational capabilities of HEM systems during the next ten years.

Survey applications introduced over the course of the last decade show clear trends toward quantitative interpretation and indirect detection of economic mineralisation. It is anticipated that this trend will continue, driven by improvements in quantitative data acquisition, better interpretation tools, and by closer cooperation between explorationists and survey contractors.

Software developments and improvements in computer technology have coupled with new sensor development to create novel capabilities, such as real time inversion for sea ice measurements. While this particular application has no direct impact on mineral or groundwater exploration, the existence of such a capability may lead to new survey applications. More generally, software development will certainly continue to drive the development of new applications in airborne FDEM in the future. Finally, new approaches to data acquisition, such as the multigeometry, dual-domain HELITEM® system, may point the way to a fusion of the time- and frequency-domain sensor paradigms in a new generation of survey instruments.

REFERENCES

Barringer, A.R., 1987, Historical aspects of airborne electromagnetic development, *in* Fitterman, D.V., ed., Developments and Applications of Modern Airborne Electromagnetic Surveys: U.S.G.S. Bulletin 1925, 7-8.

Becker, A., Barringer, A.R., and A.P. Annan, 1987, Airborne Electromagnetics 1978-1988, *in* Fitterman, D.V., ed., Developments and Applications of Modern Airborne Electromagnetic Surveys: U.S.G.S. Bulletin 1925, 9-20.

Collet, L.S., 1986, Development of the airborne electromagnetic technique, *in* Palacky, G.J., ed., Airborne resistivity mapping: G.S.C. Paper 86-22, 49-54.

Fraser, D. C., 1981, Magnetite mapping with a Multicoil airborne electromagnetic system, Geophysics, 46, no. 11, 1579-1593.

Qian, W., J. Gamey, J.S. Holladay, R. Lewis and D. Abernathy, 1997, Inversion of airborne electromagnetic data using an occam technique to resolve a variable number of multiple layers, *in* Sternberg, B., ed, High Resolution Geophysics, University of Arizona

Hogg, R.L.S. and G.A. Boustead, 1990, Estimation of overburden thickness using helicopter electromagnetic data, *in* Fitterman, D.V., ed., Developments and Applications of Modern Airborne Electromagnetic Surveys: U.S.G.S. Bulletin 1925, 103-115.

Holladay, J.S., S. Prinsenberg, L. Lalumiere, J. Lee, 1995, *Ice Probe*™ airborne electromagnetic sea ice sensor data, *in* Misurak, K., C. Derksen, E. LeDrew, D. Barber, eds., SIMMS 1995 Data Report, University of Waterloo

Holladay, J.S., D. Wright, M.R. Crutchlow and A. Koudys, 1994, A quantitative comparison of the TIBS™ airborne bathymetry system with launch-borne acoustic soundings near Coppermine, N.W.T., *in* Proc. U.S. Hydrographic Conference: The Hydrographic Society, Spec. Pub. 32.

Holladay, J.S., J.R. Rossiter, and A. Kovacs, 1990, Airborne measurement of sea ice thickness using electromagnetic induction sounding, *in* Proc. Ninth Intl. Conf. Offshore Mech. and Arctic Eng.: ASME, Vol. VI, 309-315.

Johnson, I.M., and Fujita, M., 1985. The Hishikari gold deposit: an airborne EM discovery. CIM Bull. 78: 61:66

Macnae, J. C., 1979, Kimberlites and exploration geophysics, Geophysics, 44, no. 8, 1395-1416

Palacky, G.J., 1981, The airborne electromagnetic method as a tool of geological mapping, Geophysical Prospecting **29**, 60-88.

Palacky, G.J., and G.F. West, 1991, Airborne Electromagnetic Methods, *in* Nabighian, M., ed., Electromagnetic Methods in Applied Geophysics, Society of Exploration Geophysicists, 811-879.

Paterson, N.R., 1971, Airborne electromagnetic methods as applied to the search for sulfide deposits: Canadian Institute of Mining and Metallurgy Bulletin, **64**, 29-38.

Paterson, N.R., 1973, Airborne EM in perspective, Canadian Mining Journal **94**, 101-105.

Pemberton, R.H., 1962, Airborne electromagnetics in review, Geophysics **27**, 691-713.

Qian, W., J. Gamey, B. Lo and J.S. Holladay, 1996, AEM apparent resistivity and magnetic susceptibility calculations, Exp. Abs. of 66th SEG, 1282-1285.

Rossiter, J.R. and J.S. Holladay, 1994, Ice-Thickness Measurement, *in* S. Haykin, E.O. Lewis, R.K. Raney, and J.R. Rossiter (eds), Remote Sensing of Ice in Canada: Wiley Interscience, 141-176.

Sengpiel, K.P., 1986, Groundwater prospecting by multifrequency airborne electromagnetic techniques, *in* Palacky, G.J., ed., Airborne resistivity mapping: G.S.C. Paper 86-22, 131-138.

Ward, S.H., 1966, The electromagnetic method, *in* Mining Geophysics II: Society of Exploration Geophysicists, 224-372.

Ward, S.H., 1970, Airborne electromagnetic methods, *in* Morley, L.W., ed., Mining and Groundwater Geophysics 1967: G.S.C. Economic Geology Report 26, 81-108.

Zhang, Z., and D.W. Oldenburg, 1995, The inversion of AEM data to recover magnetic susceptibility structure in a 1-D environment, Exp. Abs. of 65th SEG.