Paper 23

Developments in Broadband Airborne Electromagnetics in the Past Decade

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ABSTRACT

During the past decade, AEM systems have further matured, and are essential tools for a wide range of mineral exploration and geological or environmental mapping applications. The product of peak dipole moment and the Liu waveform factor provides a quantitative estimate of the effective signal strength of a TEM system at a specific base frequency. Noise levels in AEM have been lowered with electronic and processing advances, to the point that external noise and suspension noise are the dominant remaining sources. There is still a need and opportunity for improvements in noise reduction. The most challenging development required of AEM is the development of systems operating at 5 Hz or less to penetrate conductive cover and assist in the discrimination of very conductive copper/nickel sulphide deposits. Altimeter errors provide the main limitations in depth resolution of shallow environmental targets. 2D and 3D imaging and inversion strategies are not yet reliable or fast enough for routine application.

INTRODUCTION

The main usage of airborne electromagnetics (AEM) remains mineral exploration, but most of the results are not published. A literature search over the past decade using Google scholar locates several hundred papers of relevance to AEM, with however very few mineral exploration case histories. The publications confirm that AEM usage has expanded significantly in the past decade from its original applications in mineral exploration and geological mapping. Systems are finding extensive use in salinity and hydrogeologic mapping (Baldridge et al., 2007, Beamish and Kurimo, 2000; Paine, 2003; Munday et al., 2004; Wynn et al., 2000). Contaminant mapping from landfills and mine tailings has also been successful (Beamish and Mattson, 2003; Hammack et al., 2002). Sea ice mapping with small helicopter-borne, frequency domain (HFEM) systems has seen considerable recent interest, (for example Pfaffling and Reid, 2007), revived from the pioneering work of Kovacs and Holladay (1990).

The state of the art in time domain airborne electromagnetics in 1997 was summarized in the Exploration ’97 volume by Smith and Annan (1997), while advances in frequency domain systems were summarized by Holladay and Lo (1997). Both papers reported that developments in AEM technology were underway, and predicted rapid progress. Proof of this rapid progress was provided in the Proceedings of the International Conference on Airborne Electromagnetics, held six months later in Sydney, Australia, with papers compiled by Spies et al. (1998) into a special issue of Exploration Geophysics (AEM 98). In AEM 98, Fountain provided a detailed and comprehensive history of the first 50 years of AEM, which paper complemented the evidence of substantial advances in hardware and software by the many other authors.

With the benefit of hindsight, the most significant of the hardware developments reported in AEM 98 were details on the usefulness of streaming receivers by Lane et al. (1998) in reducing noise, the benefits of B field measurements (Smith and Annan, 1998, Foley and Leslie, 1998), and the identification of sources of calibration errors in frequency domain HFEM systems by Fitterman. At this time too, reliable methods for the conversion of AEM data to conductivity-depth images were first being presented (Macnae et al., 1998 Eaton, 1998). Such processing is now universally applied to aid in interpretation, occasionally complemented by 1D inversions.

Also in AEM 98, progress on 2D and 3D modelling and inversion were thoroughly discussed by a number of authors, but while progress continues to be made, these procedures remain painfully slow, and are both limited and error prone as will be further discussed in this review. A comprehensive set of AEM 98 case histories provided examples that suggested that a number of challenges remained for AEM systems.

PERCEIVED CHALLENGES AT THE MILLENNIUM:

A number of issues were identified in Exploration ‘97 and AEM 98 where airborne systems were not able to meet requirements. These can broadly be classified into 6 categories, which will be discussed in detail:

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1. The spatial resolution of high-moment AEM systems needed improvement.
2. The signal/noise ratios of existing systems were insufficient to detect some targets.
3. More quantitative data was needed for better interpretation (in particular to resolve vertical layering in environmental applications).
4. Improved AEM detection of perfect conductors (Ni) and poor conductors (environmental and kimberlite exploration) was desired.
5. There were severe limitations in penetrating conductive cover and in achieving bathymetry to desired depths.
6. Fast, trustworthy and easy-to-use tools were required for interpretation for both 1D and 3D targets.

DEVELOPMENTS TO MEET THE CHALLENGES

Spatial resolution

Experience from airborne magnetics that spatial resolution can be improved by flying lower above the ground has not led to any reported development of low-flying fixed-wing systems. Altitude is constrained by safety, especially in non-flat terrain. However, the ability of helicopter-borne systems to fly transmitters and receivers at nominal altitudes of about 30 m, rather than at the order of 100 m for fixed-wing systems, has led to a surge in the number of airborne helicopter time-domain (HTEM) systems in use. Rapid developments in a multitude of HTEM helicopter systems as summarized by Sattel (2006) and elsewhere in this volume, coupled with fast modeling for isolated conductors in resistive hosts has lead to direct target drilling using the AEM data alone (Taylor, 2005). In extreme applications such as UXO detection, small systems have been developed to fly at altitudes of a few meters (Beard et al., 2003).

The problems of system and hence anomaly asymmetry with towed-bird, fixed wing systems has received some attention (Smith and Chouteau, 2006), but this has not led to markedly better spatial resolution of conductive targets. The coincident loop geometry of helicopter HTEM leads to symmetric anomalies over vertical structures, provided the transmitter and receiver loops remain horizontal. Due to pendulum effects however, the constraint is never perfect with 5 or 10 degree tilts common (Davis, 2007). There are additional advantages to flying low: in resistive terrain the potential depth of investigation to an isolated target obviously increases. Furthermore, in conductive terrain low-flying systems are better able to penetrate overburden. This last assertion will be discussed later in the paper.

One factor affecting spatial resolution is the use of “proprietary filtering” used in the noise reduction process by contractors. Unless the details of the filters are known, their effects on data, whether model or field, cannot be exactly modeled, and type-curve fitting or 3D inversion attempts are sure to be in error. AEM anomalies detected over 100 m square calibration loops on the ground, for example, are commonly tens of meters wider than those predicted and observed in raw (unfiltered) data.

Signal/Noise developments

Signal

To simplify reality, any EM transmitter can be considered to have three limiting constraints: a maximum current, a maximum voltage and a sustained power limit. The ratio Q of energy lost in heat to that used to create the (near) magnetic field that energizes any nearby conductors in the quasi-static approximation is given by (e.g. Ida, 2003):

$$Q = (R\ A^2\ T) / (0.5\ L\ P^2),$$

where R, L are the resistance and self-inductance of the transmitter loop, A is the RMS current per turn per half-period T, and P is the product of peak current and number of turns. For a conceptual 24V supplied transmitter driving a 5 turn, 25 m diameter loop with 0.1 ohm total resistance, 200 A peak current and a 50% duty-cycle, ratio Q is of the order of unity. Half the available energy is thus lost in heat in the transmitter wires, and half goes to create the on-time magnetic field. Resonant transmitters (based on the Barringer Input system patent, Fountain 1998) may recover energy from the collapse of this magnetic field into capacitor banks, and use these to later return energy to the primary magnetic field.

It would appear that, for example, Megatem, Spectrem and VTEM are all fairly close to utilizing the maximum available power from aircraft generators, and thus are close to realizing the maximum possible magnetic field output for their respective waveforms as little can be done to change Q. Since most AEM systems are off-time, the on-time transmission is only part of the story. A “full” signal analysis needs to take into account waveform shape, as the strength of measured secondary field is greatly affected by the waveform as well as the average power for any TEM system.

Liu (1998) investigated the effects of repetitive transmitter waveforms shape on the off-time secondary signal from a confined target of “long time-constant τ”, which effectively means $\tau > 0.2$ T (T being the half-period). He concluded that half-sine (e.g. Geotem, Megatem) current waveform excitation produced at most 64% of the secondary signal in the off-time as would be produced by a square pulse. A triangular current (e.g. Aerotem) waveform would produce at most 50% of the square pulse signal. Any exponential turn-on and/or ramp turn-off in the current also reduced the amplitude of the secondary response as measured in the off-time. The amplitude of secondary was determined by Liu to be roughly proportional to the area under the curve in a plot of current vs. time. The RMS current sometimes quoted in system comparisons is a measure of the heat dissipated in the transmitter loop. It is also easy to extend Liu’s analysis to 100% duty cycle waveforms such as those of Spectrem and Tempest, as it is roughly double the waveform factor for a 50% duty cycle of the same shape in the on-time.

We can then approximate the ‘effective moment’ of any AEM system measuring to delay time T with the product of the Peak dipole moment and waveform efficiency. Using internet search resources as of early 2007, the AEM systems operating at that time could be summarized in Table 1, (data also obtained from Sattel, 2006). The waveform factor used is that of Liu

(1998), namely area under pulse compared to 50% duty cycle square wave.

The analysis of received signal strength for any system in practice contains an additional element: that of geometry. Signal strength should be undertaken with reference to specific targets of interest as well as to system geometry. For example, the helicopter-slung VTEM system flies significantly lower than the Megatem and Spectrem fixed wing systems, so that the actual VTEM secondary signal from a finite target (falling off with distance as the inverse cube or greater power) will probably be the largest of the four high power systems, even though its effective dipole moment is the smallest. Numerical modelling (e.g. Raiche, 2001) is the only way to compare predicted signals for specific targets using different system geometries.

Geometrical comparisons can be made with simple EM models, for example a spherical target at depth-to-center d and a horizontal thin sheet. The ratio of secondary fields as a function of geometry can be calculated using the first moment of a sphere (Smith and Salem, 2007) or the inductive limit of a thin sheet (Macnae et al., 1998).

In the case of the red curves in Figure 1, approximating the Megatem and VTEM geometries, the HTEM system is significantly better for large conductors up to depths of 220 m, and significantly better for small conductors to depths of over 500 m. The limit in response at any depth always exceeds the ratio of effective moments, due to the lower altitude assumed for the HTEM system, and the ratio is of the order of 2 at depths of 1 km.

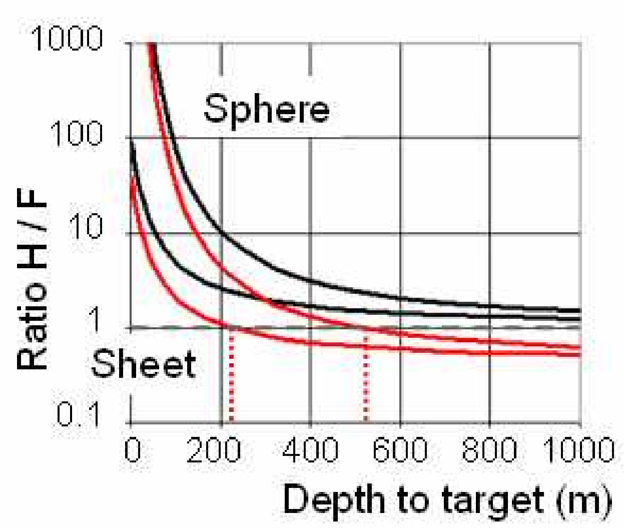

Figure 1: Ratio (black) between signals from an identical transmitter operated in HTEM (concentric, altitude 30 m) and FTEM (Tz 120 m, Rx displaced 120 m back, 30 m below) mode. Shown are the limiting cases of a compact sphere and an infinite horizontal sheet. The red curves show the ratios if the FTEM system had 2.4 times the effective dipole moment of the HTEM system.

Table 1: Airborne TEM system dipole moments as found in Sattel (2006) and on the internet, which when multiplied by the Liu (1998) waveform factor provide an effective dipole moment that can be used to compare secondary signals from a target (identically coupled at the same distance from the transmitter, with a common base frequency). With the exception of Skytem, AEM systems fall into a high signal group (> 0.5 MAm2) and a low signal group, with an order of magnitude less effective moment. This table will probably be out of date at the time of printing as systems change specifications regularly!

System	Peak Dipole Moment (MAm^2)	Liu Waveform Factor (LWF)	**Effective Moment** (MAm^2)	Base frequency range (Hz)	Notes
Spectrem	>0.5	1.9	**>1.0**	25-125	100% duty cycle
Megatem	>2	0.6	**1.2**	25-90	
Geotem	0.6 – 1	0.3	**0.4 -0.6**	12.5-125	4ms pulse, 25% duty cycle
VTEM	0.63	0.8	**0.5**	25-200	10 ms pulse, 25 Hz
High Signal^					
SkyTEM	0.12 - 0.45	1	**0.12-0.45**	25-500	50% duty cycle
Low signal ˇ					
Tempest	0.055	1.5	**0.08**	25	LWF for actual waveform with 100% duty cycle
Aerotem II	0.04	0.3-0.5	**0.01 – 0.02**	30-150	Triangular, 30-50% duty cycle
Hoistem	0.12	0.5	**0.06**	25	25% duty cycle
Newtem	0.08	1	**0.08**	25-30	50% duty cycle
Reptem					
Heligeotem	0.23 (0.5?)	0.3	**0.07 (0.15?)**	30-90	4ms pulse, 25% duty cycle
THEM	0.2	0.3	**0.06**	30	4ms pulse, 25% duty cycle

Table 2: Noise and other factors affecting AEM measurements.

Factor / source	Relative effect	Mitigation strategy	Consequence	Notes
Sferics	Diurnal, spatial and seasonal variations	Non-linear spike detection / removal, (pruning), remote reference?	Pruning causes degradation of other linear (e.g. frequency domain) filters	Peak in afternoon often causes production losses to meet noise specifications
VLF transmissions	High frequency	Notch filter, choice of base frequency	Usually not a problem	Recently observed frequency modulations limit use of notch filters
Suspension systems	Large at low frequency due to effect of rotation in earth's magnetic field	Mechanical, use larger birds and heavier sensors to lower resonance	Virtually prevent acquisition below 25 Hz base frequency	"Knocks" can occur in turbulent conditions
Sensor intrinsic noise	Increases as sensor internal resistance increases	More Cu wire in coils, or replace with Al	Heavier coils required to minimize noise	
Tow cable / electrical noise	Small	Preamp at sensor, digital or fiber-optic transmission	Avoid ancillary systems close to sensors (altimeter, attitude, GPS)	Biasing effects and synchronous effects not reduced by stacking
Amplifier / electronic instability	Affects system gain and zero levels	Use High altitude reference to estimate drifts	Non-linear effects not correctable	
Powerline	Variable	Set base frequency at odd harmonic		Switch motors cause broadening of powerline harmonics, and introduction of other frequencies
Current monitoring inaccuracy	Depends on current measurement	Use as many bits as receiver measurement and linear current sensor	Some system output degraded when normalized by poor current measurement	For deconvolution, current needs to be measures as accurately as receiver signals.
Radio/microwave transmissions	Large within a few km of tower		Non-linear effects have negated low-pass filtering attempts	
Limited number of bits affecting processing		Increase number of linear bits	B field transforms and deconvolution strategies may introduce noise	Not always improved by stacking
Bandwidth issues	The wider the bandwidth, the noisier the observed time series in TEM	Use multiple systems (as in HFEM and Skytem)	The higher the lowest frequency, the more stacking and noise reduction is possible	
Aircraft Noise	Important if DAS or other systems in aircraft, or if receiver close to aircraft	Longer tow-cables		Open-loop ringing when the voltage driving a loop is shut off, and the loop left open, has sometimes been misinterpreted as aircraft response.
Geometry variations	Primary field magnitude varies at receiver	Rigid systems (HFEM, Aerotem)	Affects primary field subtraction and compensation algorithms	

Noise reduction: Processing advances achieved and achievable

Airborne systems encounter different noise considerations from ground EM, but little has been published on the topic in the decade with the exception of a conference paper by Green and Lane (2002). Some of the factors affecting measurements are summarized in Table 2.

Noise reduction is one area where contractors seem to prefer to maintain confidentiality of the details of their process. Processes applied combine non-linear procedures such as sferic spike removal and drift correction, with linear processes such as averaging and manoeuvre compensation. Averaging times are quoted to be from as little as 0.1 seconds in HFEM systems, to as much as 3 seconds in Tempest. It should be noted that tapered or other windows are frequently used to minimize the loss of spatial resolution that would occur with boxcar averaging, but some spreading is inevitable and needs to be accounted for in numerical modelling and inversion.

Table 1 compared the effective signals from different TEM systems. No such comparison can be made from published data for a noise reduction factor for each system. The only effective method to compare noise levels is through comparative studies over similar targets, under similar ambient noise. The difficulty of performing a useful experiment is compounded by the fact that noise levels vary as a function of time of day and season of the year, and contractors regularly claim to have made improvements in noise reduction. Noise in ground monitoring systems can change by an order of magnitude from one day to the next, implying that it may be invalid to compare data collected at different times, on different days, or in different seasons.

The overall signal/noise ratio for different systems can be estimated using comparative flights over a controlled test site, such as the Reid-Mahaffey comparison conducted in Ontario (Witherly et al, 2000). However, such tests are not definitive unless the ambient noise can be monitored during each of the AEM system overflights. If similar test sites are to be established in future, I would recommend that a reference station within a few thousand km be used to monitor ambient noise. This may be an easy task since online sferic noise data, provided by government and research agencies for monitoring lightning strike location and intensity, is becoming available from a number of spatial arrays in North America and Europe. However, turbulence is also a factor that would require control in an exacting comparative test.

Accuracy:

Frequency domain

Demands from users of AEM for more quantitative results, particularly in shallow sounding, have led to a number of improvements in calibration practice. With a layout including effective bucking coils, it is impossible to measure the primary field in a frequency domain EM system. As a result, an internal or external "known" conductor is used to calibrate the system. In HFEM, the Q coil method (Fitterman, 1998) performed by an operator on ground of unknown resistivity has been largely replaced by an airborne equivalent, where the calibration coils of Resolve systems are 'fixed' in the bird with respect to the receiver coils. Evidence collected over seawater by Ley-Cooper and Macnae (2007) suggests that internal calibrations being achieved are consistent over time, but may still be in error by factors of the order of 10%. This value is better than the Dighem scale factor errors of 20 to 30% reported by Fitterman (1998) a decade ago. Brodie and Sambridge (2006) report calibration amplitude errors of up to 30% in Resolve data collected in 2002, but when altitude errors are considered, the actual calibrations are better than 10%. With a stable system and an occasional seawater or ground-loop flight, routine calibration within 1% may be routinely achievable in future. Phase errors are rare, typically within 1 or 2 degrees, but instances of 15 degree phase errors in field data have been established in some recently acquired HFEM data.

The biggest issues with AEM systems in environmental application appear to be the problems of measurement of altitude and attitude variation (Hodges et al., 2007). Attitude variations can affect results (Fitterman and Yin, 2004). Towed birds act as a pendulum, typically tilting by tens of degrees and moving several meters from their nominal or mean position. Laser altimeters rigidly attached to birds measure the 'slant range' (an overestimate of true altitude over a flat earth), often to the top of the nearest vegetation (an underestimate of true altitude). They can thus be several meters in error. Radar altimeters (commonly on the aircraft) measure the averaged distance to the first reflector, but are for example commonly in error by up to 5 m over ploughed fields (Brodie and Lane, 2003) and, depending on their specific frequency, show significant errors near open water. Figure 1 presents a comparison of laser and radar altimeters from a year 2006 Resolve survey in Victoria, Australia. The effects of bird pendulum swing on measured altitude are obvious over the flat salt pan, and the radar produces 5- 20 m errors over the Murray River, with also 5 – 10 m errors at the edge of the salt pan. A 30 m correction for tow-cable length was applied to the radar altitude before plotting.

Clearly, any CDI or inverted section based on measured altitudes may be in error by a few meters. In mineral exploration applications, 5 or 10 m in depth error is generally insignificant, but for hydrogeologic predictions (salinity, tailings leakage) the desire sub-metre vertical accuracy requires significant improvement of altimetry as implemented on AEM systems. Such altitude variations will also affect apparent resistivity calculations whenever the amplitude-altitude algorithm (Valleau, 2000) is used over resistive ground. Altitude errors may be estimated through inversion, by allowing for a pseudo-layer of zero resistivity.

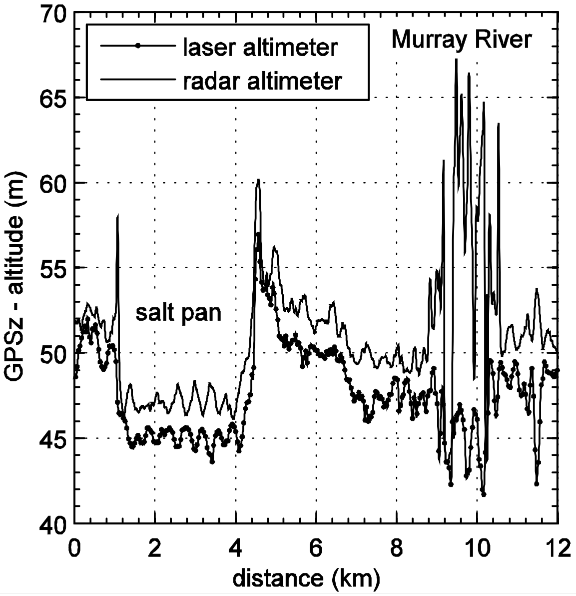

Figure 2: Laser and radar altimeter differences in a 2006 survey over the Murray River basin. Plotted is an elevation profile estimated by subtracting the altimeter reading from the GPS height of the bird.

Time domain systems

Experiments flying AEM systems over ground loops of known position and electrical characteristics have been used virtually since the inception of AEM surveying (Fountain, pers. comm.). Recently, attempts have been made to instrument such loops, and use them to calibrate both TEM and FEM airborne systems. Theoretically, it is possible to determine system geometry, amplitude and data averaging parameters from a comparison of measured data with calculated responses, aided by measuring the current induced in the loop (Davis, 2007).

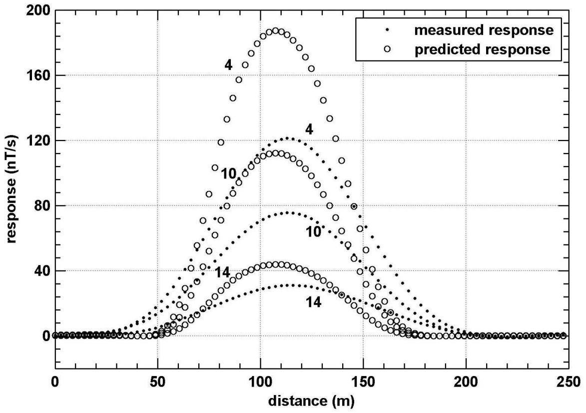

Figure 3: Observed (dots) and calculated (circles) data for channels 4, 10 and 14 of the Aerotem system flown over an 80 m square loop of inductance 695 µH , resistance 1.35 Ω and time constant τ = 0.5 ms. The prediction is narrower and smaller than the measurement, and the peaks are offset.

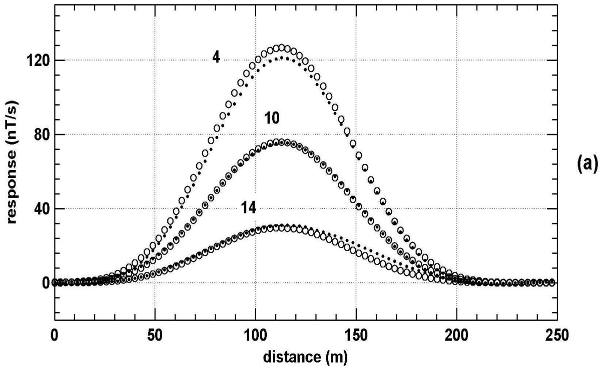

Figure 4:. Observed (dots) and fitted (circles) data for channels 4, 10 and 14 of the Aerotem system after application of 1.8 m vertical and 3.3 m horizontal shifts of the recorded AEM system location, plus the equivalent of 1.9 seconds of averaging applied to the predicted response.

Figures 3 and 4 show an example of a successful calibration test of Aerotem data. The system and ground loop geometry were known, and it was assumed that the observed transmitter current and received magnetic field values were correct, and the system was horizontal. To obtain the best fit by least squares as shown in Figure 4, the altimeter correction was predicted to be 1.8 m, the predicted horizontal shift was 3 m from the nominal location and it was predicted that the data had been averaged for 1.9 seconds. The predicted decay rate (using the ratio of the self-inductance to the resistance of the ground loop) is consistent with the observed decay from channel 4 onwards.

Systems such as Tempest and Spectrem that continuously and accurately sample the transmitted current, as well as continuously sampling the received field without bucking are the easiest to calibrate as only a high-altitude flight is needed. Towed bird systems also show pendulum effects, and as a result the systems calibration will only be exact for the geometry (or average) used in the process. Geometry is a function of airspeed, turbulence and aircraft manoeuvre.

Many TEM systems define time 0 at the start of the transmitter pulse, and commence measuring soon after the expected turn-off. Unfortunately, the length of a resonant transmitter pulse may depend on temperature, and for example in the Geotem and obsolete Questem systems, the turn-off commonly drifted by a few microseconds over the course of the day. Even though this drift time is small compared to the nominal delay time of the first channel, it has a very significant effect on amplitude. Channels in off-time systems close to the end of the transmitter pulse are often not possible to calibrate. For this same reason (waveform drift leading to estimation of a small secondary by fitting an incorrect primary), use of on-time Geotem or Megatem data generally degrades CDI sections and layered earth inversions.

In terms of quantitative interpretation, significant advances in frequency domain processing allow for the estimation of apparent dielectric permittivity and apparent magnetic permeability as well as apparent resistivity (Huang and Fraser, 1998, 2002). With geological constraints, it is also possible in limited cases to invert for the magnetic permeability of an isolated conductor (Oldenburg et al., 1997). Brodie and Sambridge (2006) show how a supercomputer cluster may be used to recover calibration factors and base-level drifts for HFEM data that are consistent with values estimated from the comparison of borehole logs and inverted sections. Ley-Cooper and Macnae (2007) show how calibration errors may be estimated statistically from historic HFEM data, under reasonable geologic assumptions. Recalibrating has led to significant improvements in the depth accuracy and reliability of CDI and inverted sections.

Data Processing: towards the step-response

It is well known that the ‘step-response’ requires less dynamic range than the ‘impulse-response” in TEM measurements (West and Macnae, 1991). Practical systems require repetitive waveforms, resulting in loss of sensitivity to slow decays than ideal step or impulse responses. In terms of AEM systems, for waveforms containing a current pulse followed by an off-time, it can be shown that B field responses are closer to the step response than are dB/dt responses. B fields further require less dynamic range to present than do the measured dB/dt responses, and B field data have responses that are more evenly weighted in amplitude towards the slow decays typical of good conductors.

Technically successful attempts to measure B field using high temperature squids were made in the 1990’s by Lee et al. (2002), but the successful commercial approach has been to calculate B fields. This has been attempted in two ways, the simplest being direct integration (Smith and Annan, 1998), where continuously sampled data are numerically summed over whole periods. This approach is taken in the Geotem and Megatem systems, and is reported to have been developed for the VTEM system. However, estimating B fields by numerical integration is band-limited, and due to discretisation limits cannot recover responses from very slow decays as discussed by Le Roux and Macnae (2007). An alternative method of dynamic range compression is the unpublished, frequency-domain deconvolution method used to convert Spectrem and Tempest data to a band-limited approximation of the ideal square wave response. These systems are intrinsically quantitative in that they are calibrated through the deconvolution process, and in my experience provide the most stable CDIs of any airborne systems.

Aeroquest on the other hand, realize an approximate step-response in the Aerotem helicopter HTEM systems through transmitting a triangular current waveform and measuring dB/dt (Sattel, 2006). This, while ideal from an interpretation and calibration perspective as the response contains both on- and off-time data, has resulted in a system with low dipole moment.

Better physical property mapping.

Mapping conductivity extremes

Conductivity is by far the most variable of geophysically measured physical properties, with earth material covering the range of 10-8 S/m (e.g. quartz) through to 107 S/m (amorphous massive sulphides). No EM system is capable of quantitative coverage over this range of conductivity, with the majority of broadband systems optimized for the 1 to 1000 mS/m conductivity range. Conductivities below this range are 'transparent' to the EM system, while higher conductivities prevent penetration of EM signals and act as 'mirrors'. To map differences between resistive materials (less than 1 mS/m), and to obtain more accurate shallow soundings, HFEM systems have extended their highest frequency well above 100 kHz, where 1 degree of phase is equivalent to a time resolution of a few nanoseconds. No TEM systems have achieved this resolution, although it is theoretically possible to achieve similar time constant discrimination in TEM using on-time data. Time base stability and dynamic range issues have prevented discrimination much better than 10 µs in TEM systems.

In terms of the detection of high conductivity targets, the frequency domain HFEM systems with stable geometry and measurements in the on-time are able to detect perfect conductors. However, their limited dipole moments and compact geometry, coupled with instrument drift, has meant that their depth of exploration of steeply-dipping targets is limited to the order of 100 m below surface. The rigid Aerotem system should be able to detect perfect conductors in the on-time, but no published case-histories have quantitatively verified this theoretical possibility to date. The Gemini test (Macnae and Smiarowski, 2007) has been a recent development that has proven that modified EM systems can be developed that reliably detect perfect conductors.

Porosity mapping

It is well known that the bulk conductivity within earth materials is a function of mineral conductivity, porosity, fluid conductivity and degree of saturation. In many areas of the world, the salinity and electrical conductivity of groundwater within aquifers is known from sparse borehole sampling. Water table depths and to a lesser extent salinity may be reliably interpolated in sedimentary environments, to provide estimates of fluid conductivity at every AEM sounding location. These boreholes also provide a measurement of water table depth. If AEM is used to estimate bulk conductivity in a layer beneath the water table, and assumptions can be made of matrix mineral conductivity, then it is possible to estimate earth porosity within the saturated zone beneath the water table using Archie's law.

Figure 5 shows a map of apparent porosity from recent work in Australia (Ley-Cooper et al., 2006) using CDI sections derived from Resolve HFEM data and irregularly spaced groundwater samples from boreholes. The most severe salinity hazards would probably occur when both salinity and porosity are high, and the water table is near surface.

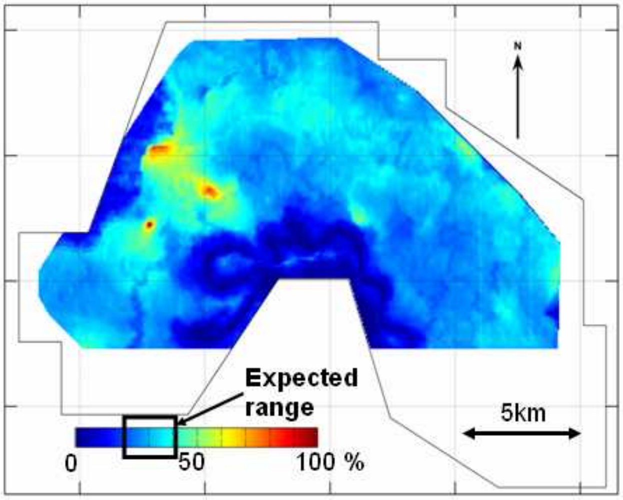

Figure 5: Predicted porosity beneath the water table of the Chowilla flood plain in South Australia, derived from detailed AEM data and interpolated groundwater conductivity samples.

Negative responses

Negative responses in the in-phase component of HFEM are a normal response of magnetic permeability; however negatives are not expected in the quadrature component. Negatives from coincident loop AEM systems (equivalent to quadrature negatives in HFEM) have been reported in a number of cases in Canada, for example the Tli Kwi Cho kimberlite (Jansen and Witherly, 2004, Witherly and Irvine, 2006). These authors have attributed negative responses from airborne HTEM data to Induced Polarization, but in order to fit the response with a Cole-Cole model, the estimated parameters appear somewhat inconsistent with ground measured IP responses. Certainly, a negative response from a coincident loop system such as Aerotem or VTEM requires that there be an energy storage mechanism in the ground, which energy then is returned at a rate slower than the EM field decay rate. This energy storage may be chemical charge storage (IP), or possibly phase change energy (as yet unexplained melting/freezing effects of induced currents at the ice-water interfaces in permafrost).

However, coincident loop negatives may also arise from energy stored in magnetic fields. An example of such magnetic field energy storage is the oscillating response obtained over an open loop of wire which is capacitively coupled to the earth. Figure 6 shows the VTEM response during flight over an open 3 turn loop in Botswana, which data was collected as part of a calibration experiment. A normal purely positive decay is seen whenever the loop is closed. When the loop is open, an oscillating response of both positives and negatives is seen, which eventually decays. We have seen the same "ringing" in airborne Hoistem data over open calibration loops and an equivalent in frequency domain with open loops over thick Antarctic ice.

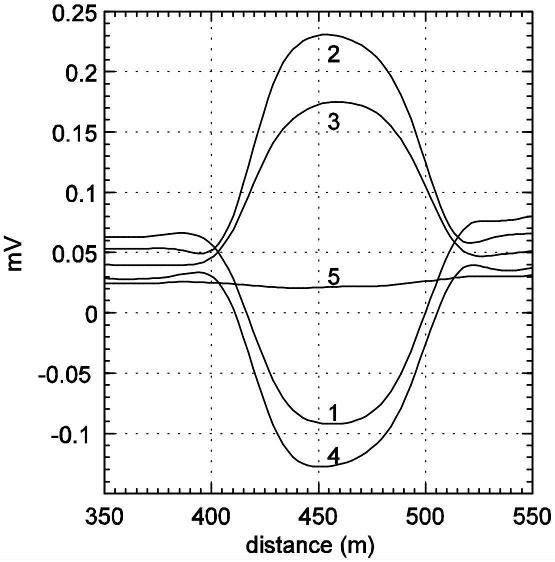

Figure 6: The airborne VTEM response detected over an open, 3 turn 100 m square loop on resistive ground. The response is negative at the earliest channel, positive for the next two, returns negative for channel 4 and is positive from channel 5 onwards. The response can be modeled as a damped resonance with ground resistance of 150 Ω, self-inductance of 13 mH, and capacitance to ground of 0.4 pF, as sampled in the receiver time windows.

Conductive cover

Conductive cover provides a severe limitation to the application of AEM. On the ground, penetration through cover can be assured by operating a low enough base-frequency, with potential detection of targets whose time-constant comfortably exceeds the time required for the primary field to penetrate the cover. Due to the comparatively rapid transit times required for fixed-wing systems, and required for economic and safe use of helicopters, there is a trade-off with averaging time and spatial resolution. If we assume 100 m is the maximum useful spatial separation between data samples, and assume velocities of 30 m/s (helicopter) and 60 m/s (fixed-wing), then the minimum usable base frequency to allow measurement of one full-cycle would be between 0.3 and 0.7 Hz. In practice, suspension system noise and the need to stack has limited useful data to 25 Hz base frequency.

Given conductive cover, compact, low flying AEM systems such as the helicopter time domain systems have a considerable advantage over higher flying fixed wing systems with towed birds. This statement is based on four premises: a) as a transmitter is reduced in altitude, the footprint of the current system induced in the ground is also reduced (e.g. Beamish, 2003; Reid et al., 2006); b) compact current systems decay more quickly than large ones implying that conductors under cover appear earlier in time (Singh and Mogi, 2003); c) the depth of penetration of a dipolar source through conductive cover is greater than that of a more uniform source (Reid and Macnae, 1999; Beamish, 2004) and d) the closer a receiver is to the transmitter, the less the effects of current gathering and the earlier in time a target response can be seen (Singh and Mogi, 2003, West and Macnae, 1991). An HTEM system at 30 m altitude would have an advantage in conductive cover penetration of at least a factor of 2 over an otherwise identical fixed wing system at 120/90 m transmitter/receiver altitude.

An alternative AEM system under development using the natural electromagnetic signals (sferics) as a source for deep conductivity mapping is the airborne AFMAG as reported by Lo et al (2006). Insufficient results are available for this system to determine its effectiveness at the time of writing.

6. Software developments including inversion/imaging,

Transformation or inversion of AEM data under 1D assumptions into stitched conductivity-depth sections is now almost universal. There are a number of algorithms available for this purpose, and a recent paper by Sattel (2005) compared results over a number of test sites. Sattel's processing of Tempest data collected over Bull Creek in Queensland is presented in Figure 7. Of the approaches tested, there is significant quantitative similarity between the alternative processing methods. In a qualitative sense, EMAX Air shows the most vertical smoothing, in that the conductive layer appears thicker than in any of the other algorithms. Clearly too, the 3-layer blocky inversion provides the poorest image over the central target where 3 layers is 'not enough'. Qualitatively, EMFlow appears to perform well with execution times of a small fraction of the inversion methods. The apparent success of the approximate methods such as EMFlow in this case can be attributed to the fact that the errors of the 1D assumption in 2D and 3D cases, coupled with calibration and altitude/geometrical uncertainty as previously discussed, are larger than the approximations made to speed up the conversion of data to conductivity-depth.

Ten years of experience in making CDI sections has led to the conclusion that the most crucial part of the CDI or inversion process is getting the system description, in particular the waveform, correct. Calibration errors, timing errors (as transmitter loops heat up during survey), inability to measure waveform during on-times, bucking problems have all been found to severely degrade the quantitative modelling of AEM data.

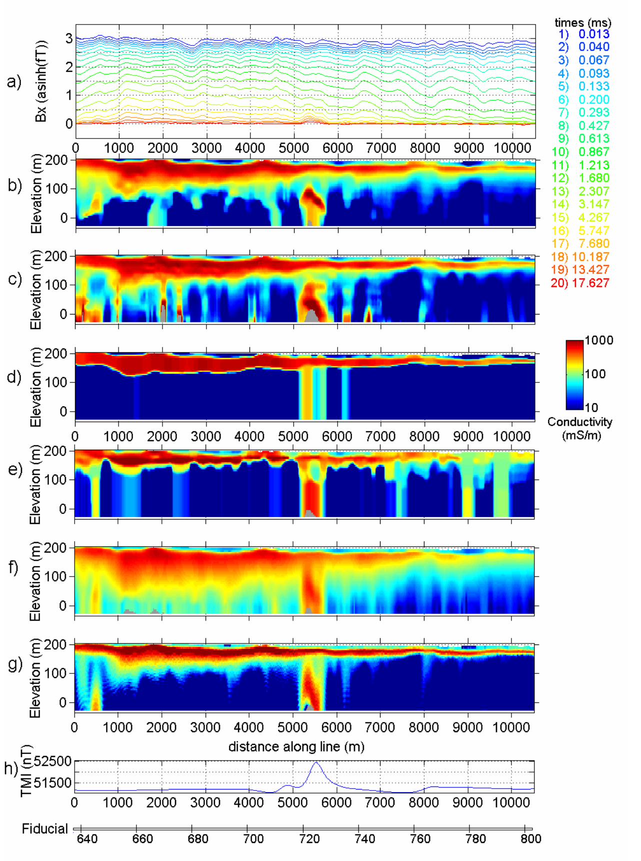

Figure 7: Processing by Sattel (2006) of a) Bull Creek Tempest data with different algorithms b) Zohdy 15 min c) Occam 360 min d) 3-L blocky 19 min e) 5-L blocky 28 min f) Emax Air 1 min and g) EMFlow 0.5 min.

Progress towards routine 2D and 3D inversions of AEM data has been slow, despite significant effort. It appears that it is possible to invert AEM data over isolated anomalies, with for example Wilson et al. (2006) showing successful recovery of input models of discrete structures and Oldenburg et al. (1997) inverting field data. Wilson et al.'s example required 15 hours of computer time to invert a segment of a few line-km of data, and while the formal inversion process is 'practical' for targets already identified as being of interest, it is unlikely to become routine in the near future as a means of processing complete survey data.

Efforts continue to find faster approximate methods for local anomaly fitting, with progress reported by Christensen and Wolfgram (2006), Zhdanov et al, (2001), Smith and Salem (2007), Macnae et al (1998) and Sattel and Reid (2001). None of these processes is reported to being routinely applied to AEM data as of this date. However, with continuing effort further developments in approximate and fast local conductor fitting are predicted over the next decades.

THE REMAINING MAJOR CHALLENGES

Conductive cover penetration

If we make a very generalized assumption that finite, dipping-target inductive limit amplitudes are likely to be 10% of that of a layer at the same depth-to-top; then no current AEM systems are capable of effective exploration below 30 S or more of conductive cover. To achieve effective exploration below 100 S of cover, typical in say Western Australia, target conductances would need to be ten times or more that of the cover, and the base frequency of the required system would need to be in the 5 Hz range. Elimination of the effects of rotation of sensors in the earth's magnetic field has been an immense challenge in the past at any base frequency below 25 Hz. In terms of spatial resolution, a 5 Hz system would probably need to fly slower than existing AEM systems, or have significantly higher dipole moment to compensate for the lack of stacking time. Reliable and useful 2D and 3D imaging / inversion of all physical properties affecting data

There have been a number of attempts to develop 2D and 3D imaging and inversion of AEM data. The inversion methods have met with some success, but with results critically dependent on starting model and at hours per anomaly, are impractical for routine application. At present, approximate methods using migration in space under quasi-layered assumptions have been presented, but these do not seem to have been sufficiently reliable to be applied in practice. Approximate methods based on spheres, dipoles or wire loops have not produced commercially successful processes to date. Existing algorithms might cynically be described as bump-detectors that add little to interpretation. I would expect significant progress in this field over next decade, and reliable 2D/3D fitting to be achieved in a few years.

Calibration and stability of AEM systems

Calibration of any AEM system is difficult on the ground, due to the presence of unknown local conductors and the impossibility of reproducing the in-flight geometry. In the 10 Hz to 100 kHz range, calibration can be achieved by collecting data over calm seawater of known conductivity and using the mismatch between calculated and measured responses to calibrate the system. Such seawater calibration does not however check on spatial sensitivity or the spatial effects of noise reduction processes, and required multiple altitude data to separate altitude errors from gain calibrations. Seawater flights at any distance off-shore require specially equipped airframes (e.g. dual engines or floats), and this may not be possible on routine survey. An alternative is to lay out a closed ground loop in a resistive location, and to compare the measured response to that calculated or fitted for the ground loop.

Practical experiments in these simple cases show that pendulum and unmeasured attitude effects have a strong influence of the accuracy that can be achieved. In his PhD thesis, Davis (2007) asserts that it is not possible to calibrate amplitudes and waveforms to much better than a few percent.

If the current induced in the ground loop is monitored, this assists in the calibration process, and has provided useful information as to actual transmitted waveforms as compared to the nominal waveforms claimed by contractors. Actual waveforms from fixed-wing systems are modified by eddy currents in the airframe, and it is often impossible with coincident loop HTEM systems to measure during the on-time without saturation or distortion of the signal due to dynamic range considerations.

Sferic noise reduction through referencing, particularly in the tropics

With the high incidence of lightning over continents in the tropics, data collected in central Africa in particular is very noisy compared to other locations. Buselli et al. (1998) showed that remote and local references could be used to improve data quality by a factor of about 4. Due to logistical difficulties and equipment costs, this research has not been commercialized to my knowledge. However, with the recent availability of inexpensive laptop based A/D converters and accurate GPS time references, this methodology should be revisited as an inexpensive means of noise reduction in such environments.

Cost reductions

Airborne electromagnetics, whether fixed-wing or helicopter, is expensive, often costing over US$100 per line km compared to about US$15 for airborne magnetic surveys. The aircraft operating costs are a significant fraction of this figure. In an effort to cut operating costs, there are reported to have been successful developments by Fugro in South Africa of an inexpensive TEM system on a single engined Caravan aircraft. Based on history (Fountain, 1998), new AEM systems are likely to continue to be developed, and lower cost is as important an issue as the desire for lower base frequency. Major reductions in cost may eventually arise through automation, with UAV platforms expected to become more economical over the next decade.

DISCUSSION

The question can be raised "Should AEM be broadband or be appropriate narrowband?" Because of the 15 orders of magnitude variation in electrical conductivity of earth materials, it is certain that the broader the band of the AEM system, the broader the range of conductivities that it can potentially detect and map. However, with finite power limitations, it is also true that the broader the band, the higher the noise within each band on average. Historically, AEM systems covered a bandwidth of about 2 decades, which has been extended to slightly more than 3 decades in current instruments. Efforts to simultaneously extend bandwidth in both the high and low frequency directions are likely to fail. Higher frequency systems need loops of low inductance, generally single turn loops in time domain. Lower frequencies require more power and multiturn loops to maximize signals. There is scope for higher frequencies in helicopter EM systems (Yin and Hodges, 2005), but dielectric permittivity response starts to dominate conductive effects in many environments. Lower frequency developments have proven very difficult due to suspension issues, but there is evidence that these suspension problems can and will be solved in the near future. If target physical properties are known, then an appropriate choice of frequency and bandwidth will outperform a choice of the widest possible bandwidth in terms of S/N and hence depth penetration and resolution.

This said, high-frequency systems take minimal power, and it is surprising that frequency domain systems such as VLF and Radiophase (Fountain, 1998) have not been used as an inexpensive "add-on" to conventional time domain systems. Such data can of course be easily included in joint inversion strategies, and help constrain the near-surface and altimeter measurement problems.

CONCLUSIONS

During the past decade, AEM systems have further matured, and are essential tools for a wide range of mineral exploration and geological or environmental mapping applications. The product of peak dipole moment and the Liu waveform factor provides a good estimate of the signal strength of a TEM system at a specific base frequency, and provides a quantitative estimate of effective signal strength. Noise levels in AEM have been lowered with electronic and processing advances, to the point that external and suspension noise are the dominant remaining sources. There is still a need and opportunities for improvements in noise reduction. The most challenging development required of AEM is the development of systems operating at 5 Hz or less to penetrate conductive cover and assist in the discrimination of very conductive copper/nickel sulphide deposits. Altimeter errors provide the main limitations in depth resolution of shallow environmental targets.

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REFERENCES

Annan, A. P., 2005, Benefits obtained from the use of a fully digital transient airborne EM system, SEG technical program abstracts 693.

Balridge, W. S., Cole, G. L., Robinson, B. A and Jiracek, G. R., 2007, Application of time-domain airborne electromagnetic induction to hydrogeologic investigations on the Pajarito Plateau, New Mexico, USA, Geophysics 72, B31-B45.

Beamish, D., 2002, The canopy effect in airborne EM, Geophysics 67, 1720-1728.

Beamish, D., 2004, Airborne EM skin depths, Geophysical prospecting 52, 439-449.

Beamish, D. and Mattsson, A., 2003, Time lapse airborne EM surveys across a municipal landfill, Journal of Environmental and Engineering Geophysics, 8, 157-165.

Beamish D. and Kurimo, M., 2003, Airborne EM footprints, Geophysical Prospecting 51, 49-60.

Beamish, D and Kurimo, M, 2000, Trial airborne EM surveys to assess minewater pollution in the UK, EAGE Conference abstracts, Glasgow.

Beard, L.P., Doll, W. E., Holladay, J. S., Gamey, T.J., Lee, J. and Bell, D. T., 2004, Field tests of an experimental helicopter time-domain EM system for unexploded ordnance detection: Geophysics 69, 664-673.

Brodie, R. C., and Lane, R., 2003, The importance of accurate altimetry in AEM surveys for land management: Exploration Geophysics, 34, 77-81.

Brodie, R. and Sambridge, M., 2006, Holistic inversion of frequency-domain AEM data without prior information , AESC extended abstracts.

Buselli, G., Hwang, H. S. and Pik, J. P., AEM noise reduction with remote referencing, Exploration Geophysics 29, 71-76.

Christensen, N and Wolfgram, P., 2006, Approximate 2D inversion of airborne TEM data, Proceedings of AESC 2006, Melbourne.

Davis, A. 2007; PhD thesis, RMIT University.

Fitterman, D., 1998, Sources of calibration errors in helicopter EM data, Exploration Geophysics 29, 65-70.

Fitterman, D. and Yin, C., 2004, Effect of bird maneuver on frequency domain helicopter EM response, Geophysics 69, 1209-1215.

Foley, C. P. and Leslie, K.. E., 1998, Potential use of high Tc SQUIDS for airborne geophysics, Exploration Geophysics 29, 35-41.

Green, A., and Lane, R., 2002 Estimating noise levels in AEM data. Extended Abstracts ASEG 16 Geophysical Conference and Exhibition, Adelaide.

Hammack, R. W., Veloski, G. A., Sams, J. I. and Mable, G. S., 2002, The use of airborne EM conductivity to locate contaminant flow paths at the Sulphur Bank Mercury mine superfund site, SAGEEP conference proceedings.

Huang, H and Fraser, D. C., 1998, Magnetic permeability and electrical resistivity mapping with a multifrequency airborne EM system, Exploration Geophysics 29, 249-253.

Huang, H. and Fraser, D. C., 2002, Dielectric permittivity and resistivity mapping using high frequency, helicopter-borne EM data, Geophsyics 67, 727-738.

Hodges, G., Munday, T, Heydorn, A. and Fitzpatrick, A., 2007, Improved mapping of conductive clays and groundwater salinity using attitude-corrected helicopter-borne EM, SAGEEP conference proceedings

Ida, N., 2003, Engineering Electromagnetics (second edition), Springer, New York

Jansen, J. and Witherly, K., 2004, The Tli Kwi Cho Kimberlite complex, Northwest Territories, Canada: A geophysical case study, SEG annula meeting extended abstracts, 1147-1150.

Kovacs, A. and Holladay, J. S., 1990, Sea-ice thickness measurement using a small airborne electromagnetic sounding system: Geophysics, 55, 1327-1337.

Lane, R., Plunkett, C., Price, A., Green, A. and Hu, Y, Streamed data – A source of insight and improvement time-domain airborne EM, Exploration Geophysics 29, 16-23.

Lee, J. B. , Dart, D. L., Turner, R. J., Downey, M. A., Maddever, A., Panjkovic, G., Foley, C. P., Leslie, K. E., Binks, R. A., Lewis, C and Murray, W., 2002. Airborne TEM with a SQUID magnetometer sensor. Geophysics. 67: 468-77.

Le Roux, C. and Macnae, J., 2007, Squid sensors for EM systems, this volume.

Ley-Cooper, Y. and Macnae, J, 2007, Amplitude and phase correction of helicopter EM data, Geophysics, 72, F119-F126.

Ley-Cooper, Y., Macnae, J. and Tweed, S., 2006, Porosity and Dissolved Salt Load Estimation from Geophysical Airborne EM and Borehole EC, AGU Fall Meeting, San Francisco.

Lo B, Kuzmin, P. and Morrison, E., 2006, Field tests of Geotech's airborne AFMAG EM system, AESC abstracts.

Macnae, J., King, A., Stolz, E., Osmakoff, A and Blaha, A., 1998, Fast AEM data processing and inversion, Exploration Geophysics 29, 163-169.

Macnae, J. and Smiarowski, A., 2007, Airborne Detection of Perfect Conductors: Project Gemini; Exploration 07 proceedings (this volume).

Munday, T., Walker, G., Liddicoat, C, 2004, Application of irborne geophysical techniques to salinity issues in the riverland, South Australia, SA SMMSP site summary report.

Oldenburg D W., Li, Y, and Ellis, R G., 1997, Inversion of Geophysical data over a copper gold porphyry deposit: a case history for Mt Milligan, Geophysics 62, 1419-1431.

Paine, J. G., 2003, Determining salinization extent, identifying salinity sources, and estimating chloride mass, Water Resources Research 3, 3-1 to 3-10.

Pfaffling, A. and Reid, J, 2007, Implications on EM Exploration Derived from HEM Sea Ice Thickness Research; Proceedings EGM2007 , Capri.

Raiche, A., 2001, Choosing an AEM system to look for kimberlites – a modelling study: Exploration Geophysics, 32, 001-008.

Reid, J. E. and Macnae, J. C., 1999, Doubling the effective skin depth with a local source, Geophysics 64, 732-738.

Reid, J. E., Pfaffling, A. and Vrbancich, J., 2006, Airborne electromagnetic footprints in 1D earths, Geophysics, 71 G63–G72.

Singh, N. and Mogi, T, 2003, Effective skin depth of EM fields due to large circular loop and electric dipole sources, Earth Planets Space 55, 301-313.

Sasaki, Y., 2001, Full inversion of electromagnetic data on a PC, Journal of Applied Geophysics, 46, 45-54.

Sattel, D. and Reid, J., 2001, Automated Anomaly Modelling of AEM Data with Magnetic Dipoles Buried Inside a Layered Earth, ASEG Brisbane extended abstracts.

Smith, R. S. and Annan, A. P., 2000, Using an induction coil sensor to indirectly measure the B-field response in the bandwidth of the transient electromagnetic method. Geophysics, 65, 1489-1494.

Smith, R. S. and Chouteau, M., 2006, Combining airborne electromagnetic data from alternating flight directions to form a virtual symmetric array, Geophysics, G35-G41.

Smith, R. S. and Salem, A. S., 2007, A discrete conductor transformation of airborne electromagnetic data, Near Surface Geophysics, 5, 87-85.

Taylor, S., 2005, Drilling from VTEM data, PDAC conference presentation.

Valleau, N.C., 2000. HEM data processing, a practical overview. Exploration Geophysics 31: 584-594.

West, G.F. and J.C. Macnae 1991. Physics of the electromagnetic induction exploration method, in Nabighian, M.N. (editor), Electromagnetic Methods in Applied Geophysics, vol.2A, Society of Exploration Geophysics, 1-45.

Wilson, G, Raiche, A and Sugeng, F., 2006, Practical AEM inversion using 2.5D modelling, AESC expanded abstracts.

Witherly, K. and Irvine, R., 2006 The VTEM heli-time domain EM system-Four Case Studies, AESC extended abstracts.

Witherley, K., Godbout, M and Irvine, R., 2000, Reid Mahaffey Field Guide, Condor Consulting.

Wolfgram, P., Sattel, D. & Christensen, N.B., 2003: Approximate 2D inversion of AEM data. - Exploration Geophysics, 34, 29-33.

Wynn, J., Pool, D., Bultman, M, Gettings, M and Lemieux, J., 2000, Airborne EM as a 3D aquifer mapping tool, SAGEEP conference proceedings.

Yin, C. and Hodges, G., 2005, Influence of displacement currents on the response of helicopter electromagnetic systems, Geophysics 70, G95-G100.

Zhdanov, M., Pavlov, D. and Ellis, R., 2001, Fast imaging of TDEM data by 2.5-D finite difference electromagnetic migration, SEG expanded abstracts 1447-1450.