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On the Origin of the HTEM Species

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ABSTRACT

By the year 2000, the airborne EM world was mainly dominated by two types of systems mounted on two very different types of platforms: the fixed wing AEM time domain systems and the HFEM systems. The idea of breeding fixed wing time domain AEM systems with HFEM systems became a reality. The objective was to get the best of the two worlds by combining the high transmitter power of fixed wing systems for depth penetration with the slower speed and flying altitude of the HFEM systems for higher spatial resolution and/or surveys over more rugged topography. During the last 5 years, the helicopter time-domain (HTEM) systems evolved rapidly to meet customer needs and finally took over their parent systems for most applications. Between 2000 and 2002, three HTEM systems were commercially operational: the AeroTEM by Aeroquest Ltd, the VTEM by Geotech Ltd, and the THEM by THEM Geophysics Inc. At about the same time, three major mining companies were developing their own in-house systems: Normandy Exploration Ltd with the HoisTEM, Newmont Mining Corp. with the NewTEM and Anglo with the ExplorHEM. A short while later, two additional systems were born: the SkyTEM of SkyTEM ApS and the HeliGEOTEM of Fugro Airborne Survey. The improvement in data quality, signal to noise ratio, depth of investigation, spatial resolution, conductance aperture and conductance discrimination, these systems achieved in such a short period of time is remarkable. However adaptation is context-sensitive; an evolutionary change that increases fitness in one exploration environment may decrease its ability to survive in another. This is why some systems have been designed to be more universal, whereas others are more target specific. In all cases, improvement in system efficiency can be attributed to major changes or fine tuning of basic specifications such as the increase of the dipole moment, a proper selection of the pulse waveform and base frequency, the possibility of measuring the on-time secondary field for B-field calculation and an efficient rejection of different sources of noise. Over the last 5 years the HTEM systems have adapted quickly and successfully to their exploration environment and to the client's needs. However clients will always need more bandwidth, better resolution and greater depth of penetration at lower cost.

INTRODUCTION

The groundbreaking book by Charles Darwin on "The Origin of Species" introduced natural selection as a process by which physical traits considered desirable are systematically favored for perpetuation. This same process can be seen in the development and evolution of the Helicopter Time Domain EM (HTEM) species over time.

The mining industry has used quite successfully airborne electromagnetic methods (AEM) for over 60 years. Witherly (2000) stated that AEM had contributed to the discovery of more than 80 major deposits. Fountain (1998) presented an excellent account of the exciting and challenging history of airborne electromagnetic development spanning a period of fifty years.

The evolution of the AEM technology and its commercial application can be closely linked not only to the surges of the commodity prices or metal cycles, but also to government mapping programs, fiscal incentives, exploration rushes following a major discovery, exploration collapse following a scandal and finally to technology breakthroughs. Carson (2003) clearly illustrates the bumpy road that the airborne geophysical services followed. He identified four evolutional phases.

The initial phase in the 1950's was extraordinarily innovative and successful with the development of a variety of in-house systems. The ensuing evolutional stages 2, 3 and 4 have each produced more mature and advanced AEM methods. The second stage was known as the fixed wing AEM era. Palacky and West (1991) stated that in the 1970s, the INPUT system, an airborne time domain system, accounted for 70% of all AEM surveys carried out in the free market and developing countries but its share declined considerably in the 1980's when demand for base metals and uranium slumped. The significant increase in the gold, diamond and groundwater exploration in the 1980's resulted in the need for a more versatile system that could map complex geological terrain with a higher resolution. The development of multi coil, multi frequency helicopter frequency domain system (HFEM) was accelerated to meet this need. The third phase saw the maturing of the HFEM species. During this period, two HTEM systems were conceived but had limited period: the Heli INPUT designed by Questor Surveys Ltd that consisted of a transmitter loop fixed around the helicopter with a towed receiver bird and the Aerodat (Hogg

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1986, 1989) systems. The first actually flew production surveys for a year or two, but proved too expensive to operate and difficult to interpret because of system asymmetry. The latter never got past the prototype stage and proved also to be too heavy for commercial operation.

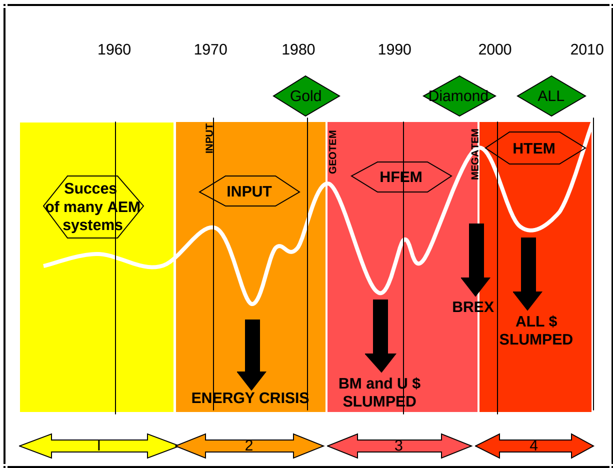

Figure 1: Evolution of the AEM systems and level of AEM activities trough time (Adapted from Carson, 2003).

By the year 2000, the airborne EM world was mainly dominated by two types of systems mounted on two very different types of platforms: the fixed wing AEM time domain systems and HFEM systems. Over the years, both species continuously evolved driven by built-in technology changes and the market demand. However basic configurations and objectives always remained the same. The powerful fixed-wing systems were employed to benefit from their large footprint and capability for deeper investigation of discrete conductors, mainly base metal and uranium deposits. On the other hand, the helicopter borne systems had a high degree of near surface resolution and were very effective in near surface mapping, but with limited depth penetration especially in those areas with conductive overburden. Both of these technologies had reached a significant level of maturity at the end of the millennium. This maturity, combined with the difficult metal market, and the fact that airborne geophysical contract services for the mining industry was for the most part dominated by a single company could have been seen as an unfavourable time for development of new technology. But it was not the case for visionary geophysicists who were prepared to take risks.

Between years 1998-2000, in order to survive in a complex EM physical environment and in a tough economic period, exploration companies and geophysical service providers needed to adapt. They had to design more efficient systems and to better understand the need of their customer. A major mutation in the flying EM species was about to happen.

Geophysicists started to think of breeding fixed wing time domain AEM systems with HFEM systems to get the best of the two worlds: combine the high transmitter power of fixed wing systems for depth penetration with slower speed and flying altitude of the HFEM systems for higher spatial resolution and/or surveys over more rugged topography. The dream was the same: update the time domain technology and to mount the system onto a helicopter platform to create the helicopter time domain system (HTEM). They knew that the accessory technologies needed were developed and available to allow for such a major development: accurate GPS location, fast 16-24 bit A/D converter, data storage capacity, data processing speed and so on.

Between 2000 and 2002, after a very short development time of only a few years, three substantially different and independent HTEM systems were commercially operational: the AeroTEM by Aeroquest Ltd, the VTEM by Geotech Ltd, and the THEM by THEM Geophysics Inc. At about the same time, three major mining companies were developing their own in-house systems: Normandy Exploration Ltd with the HoisTEM, Newmont Mining Corp. with the NewTEM and Anglo with the ExplorHEM. A short while later, two additional systems were born: the SkyTEM of SkyTEM ApS and the HeliGEOTEM of Fugro Airborne Survey. In Fountain's early 1998 50 year review of AEM there is little or no mention of HTEM systems, however in his subsequent 55 year review (Fountain, 2003) he refers to eight different HTEM operating systems.

By 2005, when the drastic increase in all commodity prices pushed diamond, uranium, precious and base metals exploration to record levels, most of the aforementioned HTEM systems had been fine-tuned and ready to collect the enormous amount of data needed to find more ore. Without any doubt, on Carson's graph, the fourth stage can be best depicted as the maturing period of the HTEM species. In their review of Electrical and EM methods, 1980-2005, Macnae and Nabighian (2005) have claimed helicopter time-domain systems have come of age and taken over from helicopter frequency domain and fixed-wing time-domain systems. Figure 2 is an estimation of the remarkable increase in HTEM survey production during the last 5 years (Fountain, Rudd and Branieski, personal communication)

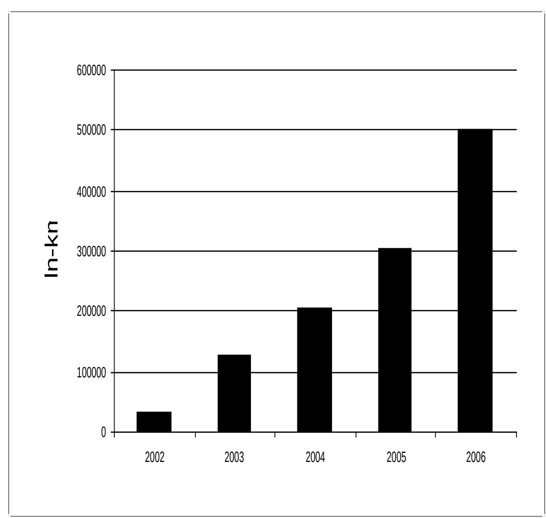

Figure 2: Estimation of the HTEM survey production during the last 5 years.

The improvement in the quality of data, the signal to noise ratio, depth of investigation and the spatial resolution these systems achieved in such a short period of time is remarkable.

KEY PRINCIPLES OF HTEM

The operating principle of a typical HTEM system is simple and similar to ground and airborne TDEM systems (Grant and West, 1965). However to fully understand the importance of the efforts applied in the HTEM system design, some basic principles of the time domain EM responses must be summarized:

1. Off-time response
   a) Weak conductors produce large responses from a rapidly decaying EM field. At the resistive limit there is no response. The solid blue line on Figure 3 represents the dB/dt response of a weak conductor to a half cosine excitation.
   b) Good conductors produce small responses from slowly decaying fields (solid red line on Figure 3). At the inductive limit there is no dB/dt response.

2. On-time response
   a) Weak conductors produce very weak to no response (dash blue line)
   b) Good conductor produces large responses (dash red line) but quite small compared to the primary field generated from the transmitter. The primary field response is superfluous because it is unrelated to the ground response. It must be removed somehow.

Figure 3 also shows that a digitization rate as high as 100 kHz produces a large amount of data per survey day. Recent development in mass storage capacity devices allows for the recording of the continuous flow of data, the fully streamed data. However, customers will commonly only see the processed data after filtering, binning and stacking of the full streamed data which is normally done in real time within the Digital Acquisition System (DAS). When fully streamed data is recorded, data can be reprocessed post flight to improve spherics and power line noise rejection that are often only smoothed out in the standard processing phase.

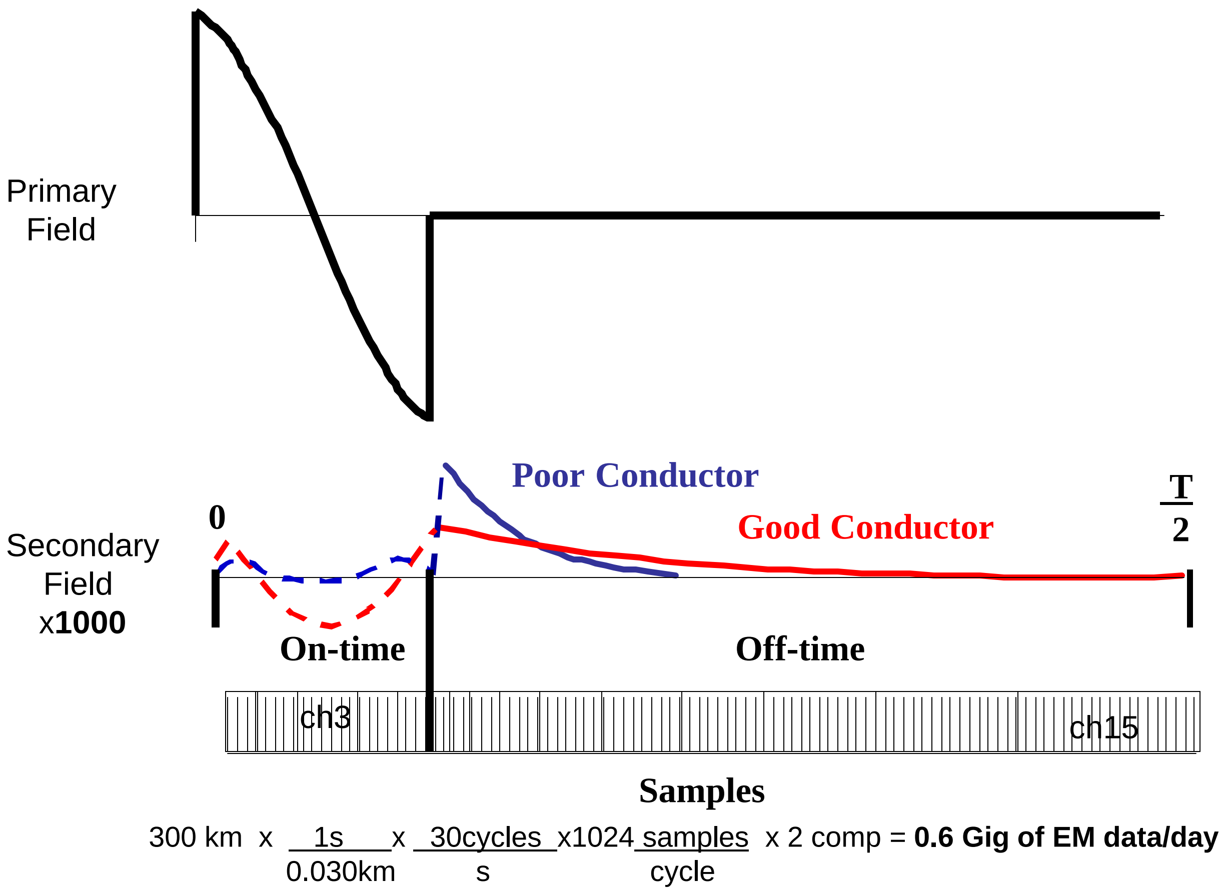

Figure 3: Basic principles of HTEM. a) For this schematic example, a receiver coil sensor (dB/dt) detects a primary EM field generated by a half sine waveform current in a transmitter (transmitter) loop. b) The primary field interacts with weak and good conductors producing secondary EM signals that are typically detected by coil sensors as two distinct responses. c) The detected signals are sampled by a fast digitization process followed by binning which consists in averaging a certain amount of successive samples also called windows or channels. The fast decaying early off-time response associated with weakly conductive zones requires a very rapid sampling rate to be accurately recovered. The width of the time gates increases approximately exponentially with delay time which helps reduce the effective noise.

DESIGN OBJECTIVES

In all cases, the new breed of HTEM systems were primarily designed for operation over rugged terrains or in areas where high resolution and fast airborne coverage were required. The objectives behind the HTEM design are similar to ground EM systems, only constraints differ. The nature of the operational constraints relate to a moving system that has to be light enough to be towed by a helicopter. Pure hardware constraints are related to the large dynamic range and bandwidth required to detect fast varying large fields, because of proximity of the receiver to the transmitter, and very small signals throughout each cycle.

The end-user evaluation of the available systems for a specific exploration project should be based on one or several of the following criteria or needs:

- Signal to noise ratio (S/N)
- Conductance aperture and conductance discrimination
- Resolution, capability to recover the conductor geometry, depth of investigation

In their evolutionary process, the HTEM systems have evolved to meet the customer needs. However adaptation is context-sensitive; an evolutionary change that increases fitness in one exploration environment may decrease its ability to survive in another. This is why some systems have been designed to be more universal, whereas others are more target specific.

When evaluating survey systems based on target types the customer must evaluate and weigh the following factors:

Signal to noise ratio

The signal/noise ratio or sensitivity is the most critical aspect when evaluating a system. The S/N notion is relative to the target response and can be difficult to evaluate in an absolute sense. Some systems will be more sensitive than others for certain targets in certain environments. For each system, the noise level varies with wavelength. The most troublesome noise occurs when the wavelength content of the noise is similar to the target anomalous response to be resolved. Noise levels will also vary from day to day depending on the weather, the geomagnetic field activities, local sources of man-made EM noise, and stacking and filtering processes. The main objective of any HTEM system design is to maximise sensitivity by increasing the target response and minimising noise.

Conductance aperture and conductance discrimination

In the early days of EM methods, in Canada at least, geophysicists divided the earth in two parts: the discrete conductor and the resistive host rock. Later, conductors were termed good or bad and geophysicists started to factor in the effect of conductive overburden. As ground and airborne EM systems improved, more complex situations were recognized and interpreted. More physical properties measurements on rocks, core samples or down hole supported and aided in the EM survey interpretation and modeling. Years of practical experience brought a clearer understanding of the targets we are searching for either directly or indirectly by means of resistivity mapping.

The Matagami zinc-rich VMS deposits are examples of how our understanding has evolved. For a long time, Matagami deposits were thought to be poorly conductive due to their sphalerite-rich nature and the fact that sphalerite exhibits low conductivity. Recent work has shown that their conductance could be as high as 1000S due to the presence of a minor percentage of a pyrrhotite or chalcopyrite within the ore body (Allard, 2004).

Target conductivity is not only related to the type of minerals or sulphides present but also to their grain size, the macroscopic texture, and the alteration overprint. Throughout the years, we learned that Ni sulphide deposits are highly conductive with conductivities frequently higher than 10 000 S (pers. comm. Tony Watts). We also now know that basement graphitic metasediments and faults associated with uranium deposits in the Athabasca basin can be as low as 1 S (Irvine and Witherly, 2006). In summary, the designers of the recent HTEM systems have had to optimize their systems to:

- Discriminate targets that have a broad range of conductivities from 1 S to >10 000 S. Traditionally time-domain ground and airborne system like INPUT were most effective in the conductance ranges of 10-500 S. The main HTEM discrete target types are now volcanogenic massive sulphides (VMS), magmatic nickel-copper, iron oxide copper (IOCG), kimberlites, and graphitic related uranium deposits.
- Identify small but significant rock mass resistivity variations. Mapping resistivity contrast is often quite important in cases such as the gold exploration or ground water search, for example.

Resolution, capability to recover the conductor geometry, depth of investigation

Continuous evolution of the HTEM systems to satisfy customer needs did not only require adaptation to detect and resolve highly variable conductive targets but also to detect and resolve various target shapes, sizes and depths. The customer needs are simple: he wants to rely on sufficient exact and accurate data to be able to plan successful drill holes by doing minimal amount of ground follow-up. More importantly he also wants to find targets that previous system failed to detect because those targets were too conductive, too deep, too short and/or had complex geometry.

TECHNICAL SOLUTIONS (MUTATIONS)

Transmitter loop – receiver coils configurations

With the exception of Anglo American's ExplorHEM system, which has a configuration similar to a frequency domain rigid boom system with a 12 m separation between transmitter loop and receiver coil, all systems have adopted either one or the other of the two following configurations:

- the coincident loop, in-loop or central loop configurations, where the receiver coils are in the center of, or very closely located with, the horizontal transmitter loop such as in SkyTEM, VTEM, AeroTEM, HoistEM systems. Anomaly shapes are independent of the flight-line direction and symmetrical for vertical conductor (Figure4).
- the vertical separated loop configuration where the receiver coils are located on the towed cable some distance above the horizontal transmitter loop. HeliGEOTEM, NewTEM, THEM uses this configuration. Because of the drag, the receiver coils are always a short horizontal distance ahead of the transmitter loop causing a slight asymmetrical effect on the anomalous profiles
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All HTEM systems produce much larger amplitude responses for flat lying conductors due to a transmitter-Target-receiver optimum coupling geometry. On the other hand, vertical plate-like conductors caused anomalies that are much smaller as shown on Figure 4. This must be carefully taken into account when depth of investigation specifications are evaluated. To better couple deep vertical conductors, THEM spent a considerable amount of efforts to fly a horizontal loop configuration system where the receiver coil was towed in a blimp about 50 m behind the transmitter loop (Bodger et al, 2005).

Some systems (AeroTEM, SkyTEM, HeliGEOTEM) have two receiver coil orientations: a horizontal coil that measures the vertical EM component and a vertical coil having its axis aligned with the flight line direction that measures a horizontal component. These two coil configurations provide important information on the conductor geometry as shown on Figure 5

Acquiring high quality horizontal component data is a challenge especially for systems where the receiver is attached to a rigid transmitter loop frame as in the AeroTEM and the SkyTEM. When the transmitter loop swings and rotates over conductive ground, a significant percentage of the strong anomalous vertical response is recorded in the X component receiver coil whose axis tilts away from the horizontal plane. Tilt meter measurements on the transmitter loop frame must be used to calculate compensation.

A **B**

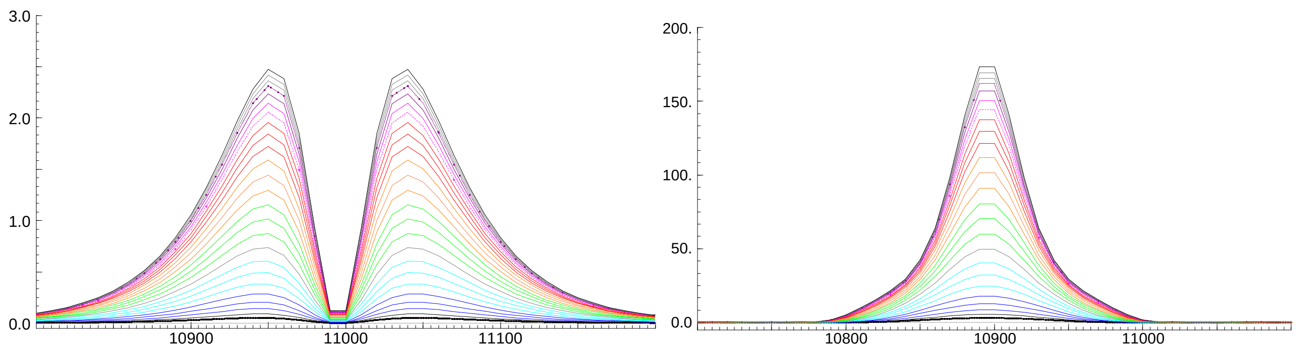

Figure 4: dBz/dt off-time typical anomaly shape detected by an in-loop system over a) a vertical 200 m x200 m thin plate conductor located at 11000 b) a horizontal 200m x 200 m thin plate located between 10800 and 11000. Note that the difference in the vertical scale between the two plots.

A **B**

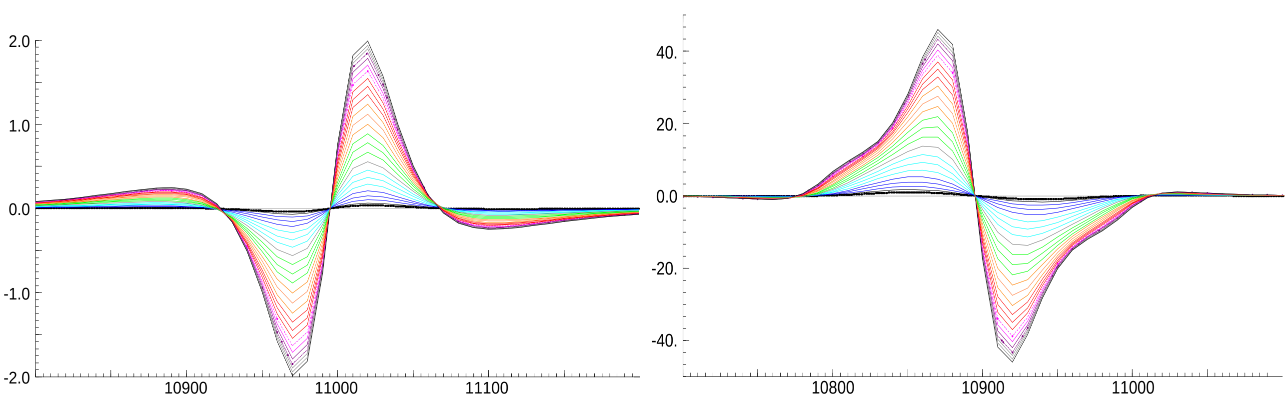

Figure5: Off-time typical anomaly shape detected by an in-loop system over a) a vertical 200m x 200 m thin plate conductor located at 11000 b) an horizontal 200 m x200 m thin plate located between 10800 and 11000.

On-time vs off-time, dB/dt vs B-field

In order to increase their bandwidth, efforts have been deployed to develop systems that have good sensitivity in the on-time in addition to the off-time by either measuring the time derivative of the magnetic component (dB/dt) or the magnetic component of the EM field directly, commonly called the B-field (Smith and Annan, 1998).

Weak conductors produce large early off-time responses that rapidly decay to zero. Because induction coils measure dB/dt, they are still the best choice of receiver sensors for these targets. The situation is different for good conductors, which generate small slowly decaying off-time responses. B-fields are therefore better suited than dB/dt to detect slow-decaying targets. Currently Spectrem Air is working jointly with AEROQUEST to implement a SQUID sensor into the AeroTEM III system (Le Roux, 2007) to directly measure the B-field. It can also be indirectly measured by a real time data integrator that actually calculates the B-field (HeliGEOTEM and VTEM). The calculation/transformation integrates the dB/dt response over the full waveform and therefore requires on-time measurements (Smith and Annan, 2000).

On-time data recording and processing are difficult because the receiver sensors measure the response from the ground in addition to the primary signal from the transmitter. It requires a large receiver dynamic range and special strategies to prevent the strong primary signal from saturating the receiver amplifiers or disturbing their linearity. In the case of the NewTEM, THEM and HeliGEOTEM, the receiver coils are situated several meters above the transmitter loop. In the SkyTEM system, the receiver Z coil is located at the edge of the transmitter loop with a 1.5 m vertical separation in a null coupling position and the receiver X coil is 2 m behind the transmitter loop also in a null coupling area. The VTEM system has a 3 m radius bucking coil located in the center of the transmitter loop and around the receiver Z coil to reduce the primary field strength

Even if a good conductor produces a significant in-phase on-time response, this response is still quite small relative to the primary field when the receiver coil is located in close proximity to the transmitter loop. Primary field removal is therefore critical to isolate the secondary response during the on-time. Three approaches have been proposed

- The primary field can be easily calculated and removed when the transmitter loop-receiver sensor geometry is rigid and perfectly known and when the waveform current in the transmitter loop is precisely recorded. This ideal methodology is still not practical for continuously moving airborne systems where the recorded primary field changes continuously, ie no system is rigid enough to allow for a precise enough primary field subtraction. This is only achievable for ground EM surveys with static geometry.
- The primary field is approximated by a high-altitude reference waveform continuously scaled to best fit the total on-time response. This accounts for the variation of amplitude of the transmitter pulse with temperature and other factors throughout the day. However, this process used by Fugro for the HeliGEOTEM, also eliminates the in-phase secondary response which constitutes the major component of the good conductor response leaving just the least diagnostic quadrature component (Smith, 2001).
- For the AeroTEM system, Balch (2003) explains how the primary field removal problem is overcome. First the response of a bucking-coil properly located on the transmitter is subtracted from receiver coil Z response reducing the primary response from 109nT/s to 103nT/s. Second a post-processing algorithm that includes a deconvolution of the system's current waveform reduces further the residual primary field signal. This procedure does not consider the fact that that some of the secondary field is measured and also removed by bucking-coil subtraction.

Pulse Waveform and base frequency

As studied by many authors (Smith 1998, Lui 1998, Stolz and Macnae 1998), the transmitting current waveform and the base frequency play an important role on the intensity of the induced EM ground response. To meet precise objectives and strategies, each group selected a specific waveform at one or more base frequencies (Figure 6).

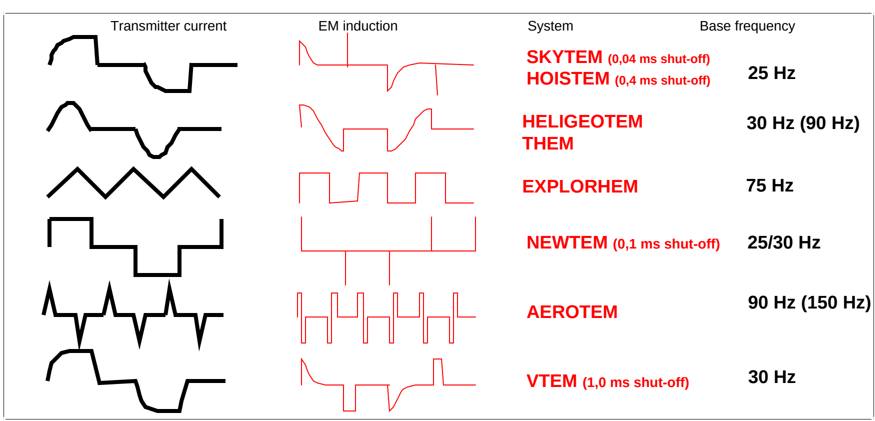

Figure 6: Schematic representation of the various current waveforms used by the HTEM systems. The primary EM field detected by the receiver coil is proportional to the time derivative of current waveform.

System bandwidth is mainly determined by the frequency content or power spectrum of the primary EM field and is not directly related to the system base frequency. All other things being equal, a fast transmitter current shut off produces a primary EM field containing high frequency harmonics. Such a waveform will generate early off-time responses in weakly conductive zones allowing near surface resistivity mapping.

On the other hand, a slow and long shut off transmitter current penetrates deeper in the ground and induces secondary currents in good conductor. It also induces less response from the relatively weaker conductive host, enhancing the high-conductivity target.

Dipole moment

Raising the transmitter dipole moment is a common practice to increase the response amplitude in order to detect conductors at greater depth. During the evolution of the HTEM systems, the steady increase in loop sizes, number of loop turns and transmitter current resulted in a spectacular mutation (Figure 7). However, compared to fixed wing systems, the necessity of smaller and lighter equipment will always set a certain limit to the transmitting power. The power source employed could be the helicopter power system itself (AeroTEM, VTEM), a motor generator which is fixed to transmitter loop (HeliGEOTEM, THEM, or SkyTEM) or on the towed cable between the helicopter and the transmitter loop (SkyTEM) or attached to the helicopter skids (HoisTEM).

If the survey objective is to map the near surface conductivity, then a lower dipole moment with a faster turn off is more appropriate. Most of the systems are adjustable. By using only one or two transmitter loop turns, the loop impedance is reduced allowing a lower dipole moment and a faster turn off time.

Type of noise

The types of noise affecting HTEM are multiple but the main sources are:

1. the receiving coil moving in the earth magnetic field
2. the secondary response from the helicopter itself or other parts of the system (parasitic noise)
3. Spherics and VLF fields
4. the wide band thermal noise from the coils themselves and electronics used to condition the signal

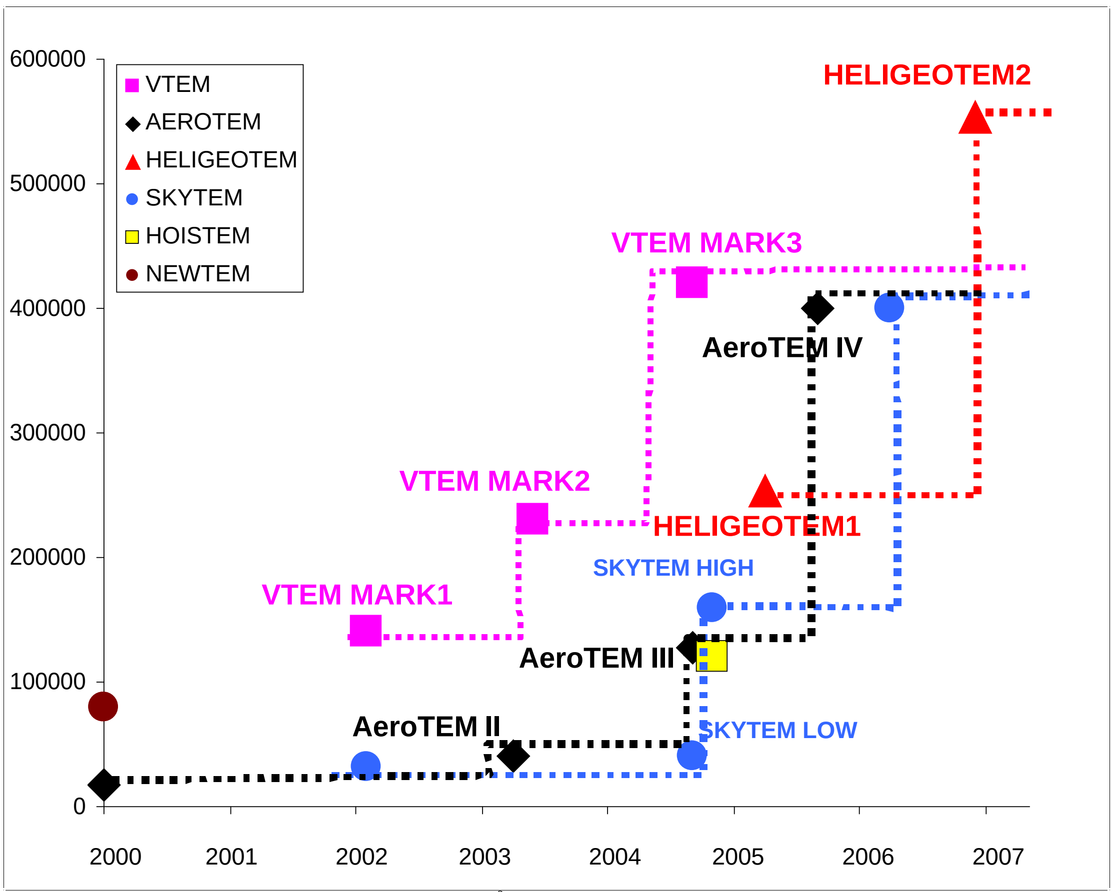

Figure 7: Graph showing the steady increase in dipole moment (Am^2) for all HTEM systems during the last 5 years

Coil motion noise

For all AEM systems, receiver coil movement in the earth's magnetic field produces a parasitic signal that can be of relatively large amplitude (Annan, 1983). This phenomenon is observed when:

- Coils slowly swing or rotate relative to the earth's magnetic field direction;
- Coils move and vibrate in the wind and the turbulence of the helicopter;
- The helicopter changes speed for example when climbing or descending in rough terrain;
- The tension in the towing cable is not steady causing knocks to the coils;
- Amplitude and direction of the earth's field is locally disturbed.

Figure 8 shows how the coil movement noise affects the raw full stream data. In general, when oscillations are not too rapid, proper filtering brings the base line to zero. It becomes more complex at lower transmitter base frequencies when bird motion noise frequency content approaches the system base frequency. This explains why good weather and mechanically stable receiver coil mounting are critical during data acquisition. For instance, receiver coil suspension is often more of a top-secret art than sound science.

Secondary response noise

In fixed wing systems, the transmitter loop surrounds the aircraft that creates a significant secondary field from the metallic airframe, which varies with the pitch, roll and yaw of the plane. A compensation algorithm is necessary to correct for this unwanted signal. In HTEM systems, the transmitter and receiver are far enough away from the helicopter to consider these effects as weak and constant. The compensation procedure consists simply of measuring the system response in high altitude before and after each flight and then deconvolving this system response from the measured off-time response. The high altitude calibration causes some logistical constraints since it requires the flight conditions to be clear up to typically 600 m to 800 m.

Spherics and VLF noise

Spheric activities could seriously degrade data quality of HTEM surveys flown in summer or rainy seasons when intense electrical storms are quite active at continent scale. An example of how a spheric pulse affects a full-stream data record is shown in Figure 9. In principle, spheric amplitudes of horizontal components are 5 to 10 time larger than the vertical field, since Hz is only produced by local sources or heterogeneities in crustal conductivity. When many spheric events are present, filtering is a difficult task since their amplitude and time distribution are essentially random. Bouchedda (2005) proposed a very effective way to eliminate the spherics before stacking based on a multi-resolution wavelet analysis. His technique consists of detecting the spherics followed by their removal. This technique possesses an obvious advantage over the standard interpolation methods, which are not generally successful when spheric activity is intense

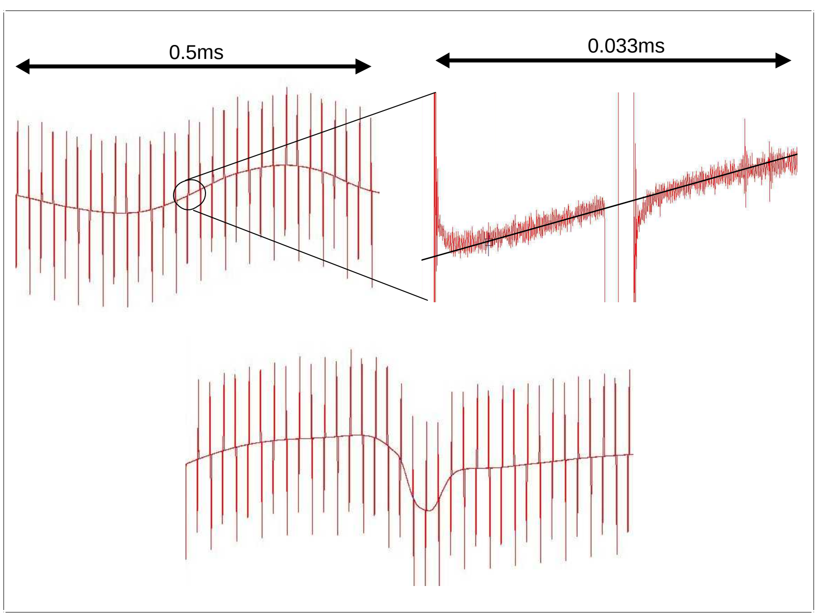

Figure 8: Noise related to bird motion. a) The receiver coil movement induces a relatively low frequency signal b) the slowly oscillating baseline can be approximated by a quasi-linear function during each cycle. It is easily removed by high pass filtering. Note the weak anomalous fast decaying response following the transmitter shut off. c) a very rapid receiver coil oscillation causes a sharp baseline bend. This type of noise is very difficult to filter out without affecting the weak anomalous secondary signal.

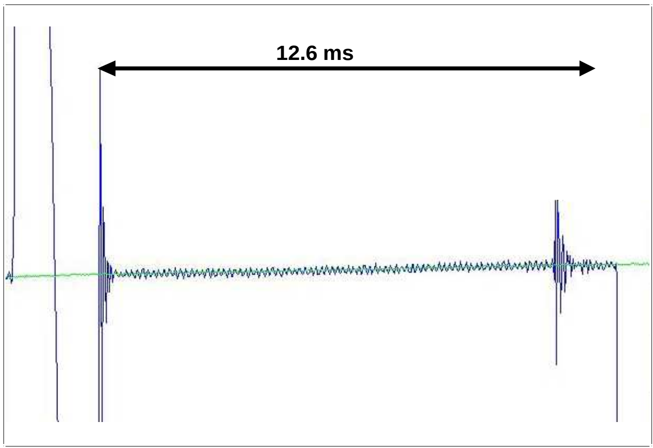

Figure 9: Example of a spheric burst that was detected at the end of an off-time period. On average a spheric lasts less than 1 ms

VLF noise, like the spherics noise, affects mainly the horizontal components. Since VLF are radio waves in the 15-25 kHz frequency range, their effect is eliminated by a notch filter or significantly reduced by averaging during the stacking process.

Noise reduction

Stacking data is a very effective mean to improve signal quality. Ground surveys have a definite advantage over aero surveys since data can be stacked at the same position for a long period. Compared to AEM systems, the HTEM systems fly slower at a speed of about 30 m/s, collecting and stacking 2 to 3 times more data per km.

The stacking time window is critical for spatial and conductance resolution. A small number of stacks allows for good near surface horizontal spatial resolution but low signal to noise at late time. A large number of stacks excessively smooth the data limiting the near surface resolution but allows a better quality of data at late time for conductance discrimination. Stacking done over a period of time of about 0.25 s or a distance of about 6 m seems a good compromise. Auken and Sørensen (2006) suggested having a longer stacking period for the late time acquisition data relative to the early time in order to obtain good near surface resolution in the early time and increase the late time signal to noise ratio.

Intelligent stacking based on statistical analysis of the data is not routinely applied to the data. However significant data improvement could be obtained when spikes or bad data that exceed certain thresholds are automatically removed.

To improve the penetration depth and sensitivity to high conductance targets, a common practice has been to lower the frequency content of the transmitter waveform. This is usually done by increasing the pulse length and by lowering the base frequency, which reduces directly the noise rejection capability of the stacking process. For example when the frequency is lowered from 90Hz to 30 Hz, the number of stacks decreases by a factor of 3 and the relative white noise level increases by a minimum of 3 or about 70%. This estimate does not account for other complex noise sources such as the bird motion noise which is relatively higher at lower base frequency.

A practical way to evaluate the system noise level is to calculate the standard deviation or visually estimate noise envelope of the latest off-time window if we assume that near surface geological noise has vanished. The late time noise is a best-case scenario since early time noise is always relatively higher since less samples points are averaged in the binning process. Based on this definition, Figure 10 demonstrates how the VTEM system noise level has significantly been reduced over the last four years. To allow a fair comparison, data has been normalised to the transmitter dipole moment and to the receiver coil effective area. Plot scales were kept constant. Data are from surveys in the Matagami area over the Caber ore body, which is a small 1.3 Mt massive sulphide blind deposit located 120m below the surface. The deposit was discovered in 1994 by BHP Minerals Canada Ltd.

The 2003 survey failed to detect the Caber deposit primarily because the anomalous signal was too weak but also likely because too much filtering was applied to suppress the high frequency noise content. Some of the valid response may have been removed by the noise filtering process. The 2005 data was collected by a system that had a three times higher dipole moment. The deposit was then clearly detected. Even at the relatively large depth of 125m, the double peak shape response typical of a plate-like conductor is observed and the asymmetry of the anomaly correctly indicates a steep dip to the left. The early time channels are relatively noisy compared to the late time noise, which is relatively lower at about 0.001 pV/Am^4. At the latest time channels, the anomaly is barely above noise level. The presence of thick conductive cover to the left of the profile is marked by high amplitude of the earliest off-time channels. Prior to the 2006 survey, Geotech implemented on-time measurements allowing B field calculation. Even if the dipole moment remained the same as in 2005, the anomaly amplitude is about half of the 2005's in part because the survey was flown by error 15 m higher than planned. Late time profiles show the same noise level, in the order of 0.001 pV/Am^4 whereas the early time noise appears significantly improved. The B-field profiles show a noise level of 0.003 fT/Am^4. The early time response of the less conductive overburden response is suppressed relative to late time response of the more conductive sulphides. The S/N ratio of the late time, slowly decaying B-field response associated with a good conductor is clearly higher than the late time dB/dt S/N. However, this late time S/N is still not high enough to provide any geometrical information on the target, which can only be interpreted on the mid time channel profiles.

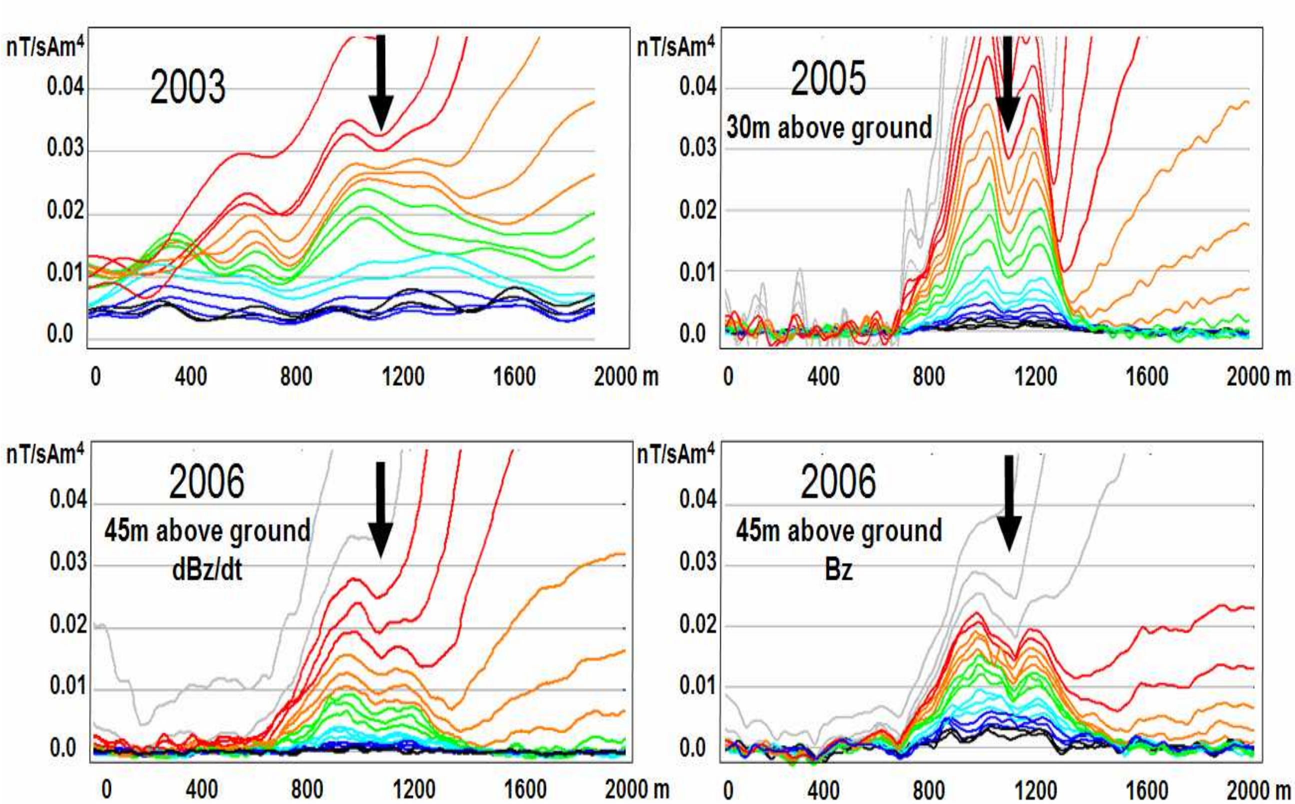

Figure10: VTEM staked profiles from surveys flown in 2003, 2005 and 2006 over the Caber deposit which is located by the arrow. The red profiles are early off-time and the blacks are the late off-time. Significant improvement in the noise level can be observed between 2003 and 2006

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Conductance aperture and conductance discrimination

The conductance aperture is defined as the effective range of conductance detectability. Factors such as waveform, noise level, dipole moment, and type of measurements determine the conductance aperture of each system. Plate modelling results combined with an evaluation of the late time noise level (Figure 11) indicate that significant differences exist between systems in their ability to detect low or high conductance zones. In all dBz/dt cases, the best S/N ratio occurs in the 10-100 S range. The peak response for a 10 S target occurs in the early off-time and the 100 S peak response in the late off-time. For the HeliGEOTEM Bz case, the best S/N is slightly shifted to higher conductances around 75 S-200 S. SkyTEM is very effective in measuring the fast decaying early time anomalous responses related to low conductance targets as low as 2 S since it has more early time windows and a fast turn-off. The VTEM has a very high S/N which gives the system the largest conductance aperture from 2 S to more than 5000 S.

The HelioGEOTEM B-field response shows a clear skew towards the high conductance range but its noise level limits its ability to detect targets above approximately 1000 S. It is worth saying that SkyTEM noise was estimated with data stacked over 32 half cycles (0.64 s or 12 m at 20 m/s) whereas HeliGEOTEM data was stacked over 15 half-cycles (0.25 s or 6 m at 30 m/s).

A drop in the base frequency or longer ramp time increase the conductance at which the peak response occurs. However, a respectable noise levels is much more difficult to achieve at lower frequency as shown by the AeroTEM example (Figure 12). The peak response has effectively moved to the higher conductance as predicted. However despite a 3 times higher dipole moment, the 2005 version of 75 Hz AeroTEM III system appears to have narrower conductance aperture and generally a lower S/N that the 150 Hz AeroTEM II.

Depth of investigation

It is well known that huge exploration potential remains at depth for blind or buried deposits. Among them are the uranium deposits in the Athabasca basin. Irvine and Witherly (2006) demonstrated that conductive graphitic metasediments and faults in the basement associated with uranium deposits can be detected by a HTEM system to depths approaching 1000 m.

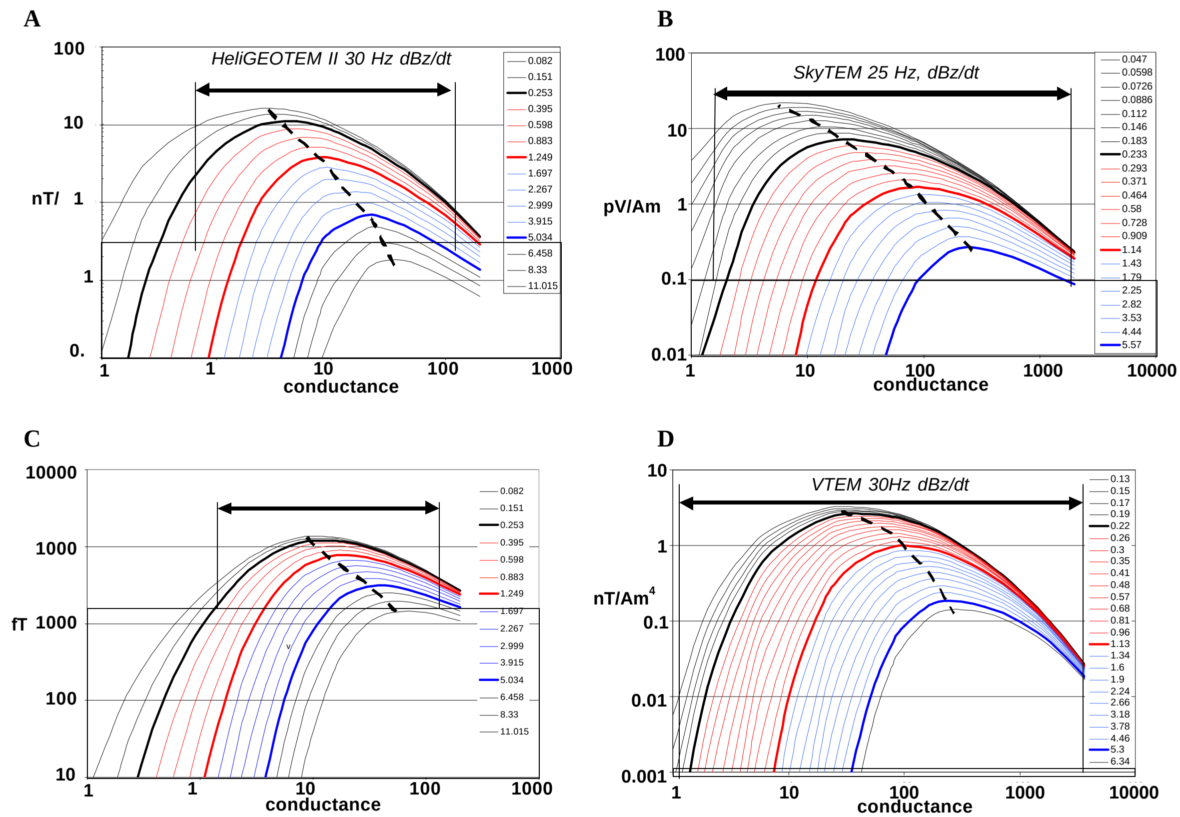

Figure 11: Off-time anomaly amplitude calculated for a 200 m x200 m vertical plate at 10m below surface as a function of its conductance a) the HeliGEOTEM II 30 Hz dBz/dt, b) the SkyTEM 25 Hz, dBz/dt ,c) HeliGEOTEM 30Hz II Bz d) VTEM 30Hz dBz/dt. Early time responses are shown in red, mid time responses in blue. Amplitudes in the grey zones are below late time noise level as estimated from actual 2006 commercial surveys. The late time noise levels are subject to change as the systems will evolve.

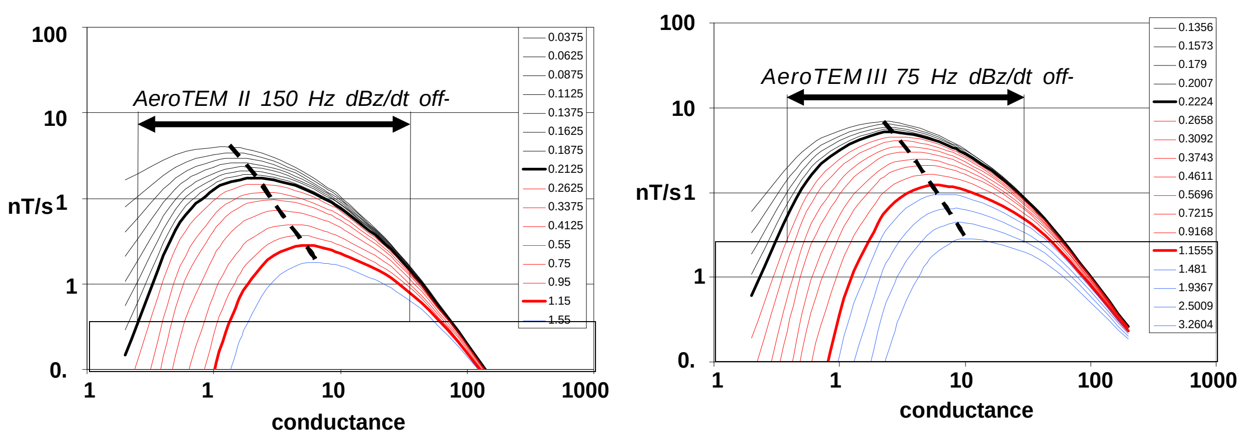

Figure 12: Off-time anomaly amplitude based on modelling of 200 m x200 m vertical plates at 10m below surface as a function of their conductance for the AeroTEM II and III

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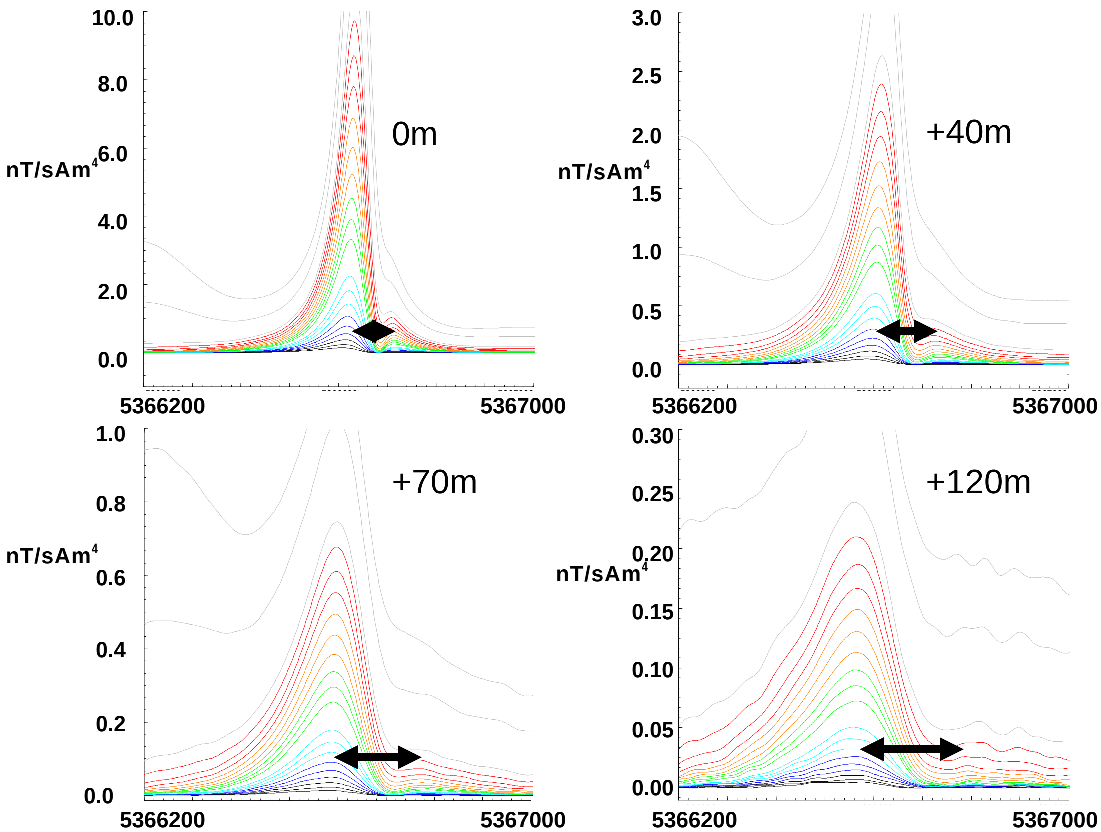

Figure 13: VTEM profiles over the Iso-Magusi deposit at different altitudes relative to the nominal flying height. The distance between the two anomalous peaks increases with flying height.

Another approach to evaluate the depth of investigation of a system is to perform a height attenuation test over a known target. When host rocks are highly resistive, flying at higher altitude has a similar effect that having the conductor buried deeper in the bedrock. The Iso-Magusi VMS deposit was often used as a geophysical test site (Telford and Becker, 1979 and Cheng et al, 2006a). The subeconomic orebody that was discovered in 1972 is located about 30 km north-west of Rouyn-Noranda. It has a sheet–like shape of 500m strike extent; 800m dip extent and a maximum thickness of 35m. It subcrops beneath 10 to 20 m of glacial cover. A previous EM survey interpretation estimated its conductance to about 55 S (Cheng et al, 2006b). A height attenuation test was performed by Geotech in 2005 over the Magusi River deposit. Test results are presented in Figure 13. This kind of test does not take into account the effect of the conductive overburden but in the Iso-Magusi case the effect is small after 1.0 ms in the off-time. Even at 120m above normal flying height, the anomalous response amplitude is still strong. The profile asymmetry is clearly visible indicating that dip information can be extracted even at relatively large depth. In this case, dip is to the left at about 45^0. The anomaly wavelength and the distance between the small and large shoulders increases with depth as expected.

Figure 14 shows the graph of the amplitude decreasing with height. Clearly a few more height steps would have been necessary to fully evaluate the maximum depth of detection. Conservative exponential extrapolation suggests that all channels would have been above noise level at a height of 150 m above normal. At 250 m, responses from mid-time channels, which are not affected by the conductive overburden, would have still been above noise level. At 350 m, the anomaly would have not likely been detected.

The geometrical and physical interpretation of detected anomalies may be quantitative or qualitative. Svilans (2006) developed a method for interpreting discrete conductors from AeroTEM profiles. From a suite of forward modeled results, empirical relationships were established between discrete conductor properties, for instance: dip, depth, dip extent, conductance and position and indicators measured from actual EM responses such as relative positions of peaks and troughs.

Sattel (2006) presented cases where derived conductivity depth sections of data acquired with five different systems successfully outlined the locations of mineralised zones.

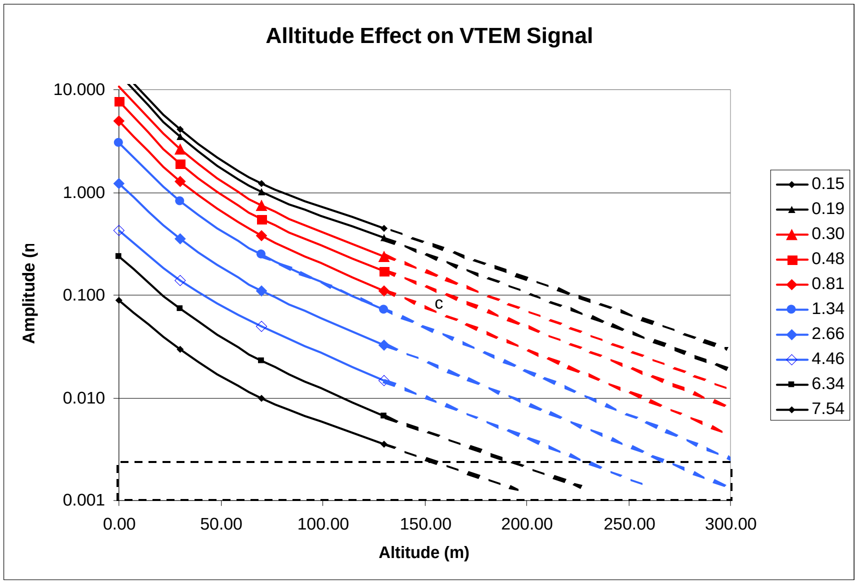

Figure 14: Graph of the amplitude of the VTEM anomaly over the Magusi River deposit decreasing with flying height. The grey area corresponds to the noise level

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Case Studies

During the year 2002 and 2003, HLEM, AeroTEM, VTEM and MEGATEM surveys were carried out over the Montcalm deposit. This Ni-Cu massive sulphide ore body (estimated resource of 7 million tonnes of sulphide of which 3.2 million tonnes grading 1.56% nickel and 0.75% copper are proven and 1.7 million tonnes grading 1.44% nickel and 0.70% copper are probable) was discovered in 1976 by drilling an HFEM EM anomaly (Fraser, 1978). Profiles over the sub-outcropping part of the deposit are shown on Figure 15. The profiles demonstrate the high resolution of the two HTEM surveys. The single peak shape indicates the conductor is not a thin sheet but rather bulky. The W shape of the HLEM profiles suggest a short dip extent of the conductor directly below the profile relative to the transmitter-receiver separation which was 200m.

The original DIGHEM anomaly was an isolated 154 S conductor when flown parallel to the strike of the deposit. A follow-up survey flown perpendicular to the target detected a 330 S target (Dighem calculations). The horizontal loop survey gave results above the inductive limit of the lowest frequency (>500 S). These two different estimates illustrate the difficulty to estimate the real conductance of highly conductive zones.

Analysis of the decay curves (Figure 16a) of the three time domain systems gives quite interesting information on the conductance discrimination of the HTEM systems. Time constants were calculated using successive sampling points and then plotted against sampling time (Figure 16b). Slight differences in the time constant curves can be observed in the overlapping off time. They could probably be related to differences in the transmitted waveform. The AeroTEM system, which has the higher frequency content, produces relatively lower time constants. Most importantly is the fact that, even at late time, the responses are still not exponentially decaying which indicates that the responses are far from the restive limit which is the very late time or zero frequency ideal case. However extrapolation of the time constant curves to the horizontal asymptote can provide better discrimination of the relative conductances.

The possibility of flying parallel to conductive formation is an other interesting feature of the HTEM since systems are symmetric and responses are independent of flight line directions. The maps shown on Figure 17 illustrate how a HTEM survey effectively detailed a formational conductor that was previously detected by a regional fixed wing AEM survey (Figure 17a). The HTEM survey (Figure 17b) was flown parallel to strike to cover a minimum amount of ground. Line spacing was tight near the conductor axis (50 m) and wider further away (100 m) to recover the full anomaly shape. A 500m wide band was therefore cover instead of the 2 km band that would have been normally flown at the required minimum flight length. With accurate GPS, flight lines do not have to be strait but smooth curve paths could be easily flown by the pilot. Resolution was accurate enough to 1) correctly detect the difference in the relative size of the two peaks suggesting a thin sheet conductor dipping to the south-east; 2) clearly map sharp discontinuities and variations in the anomalous response along strike.

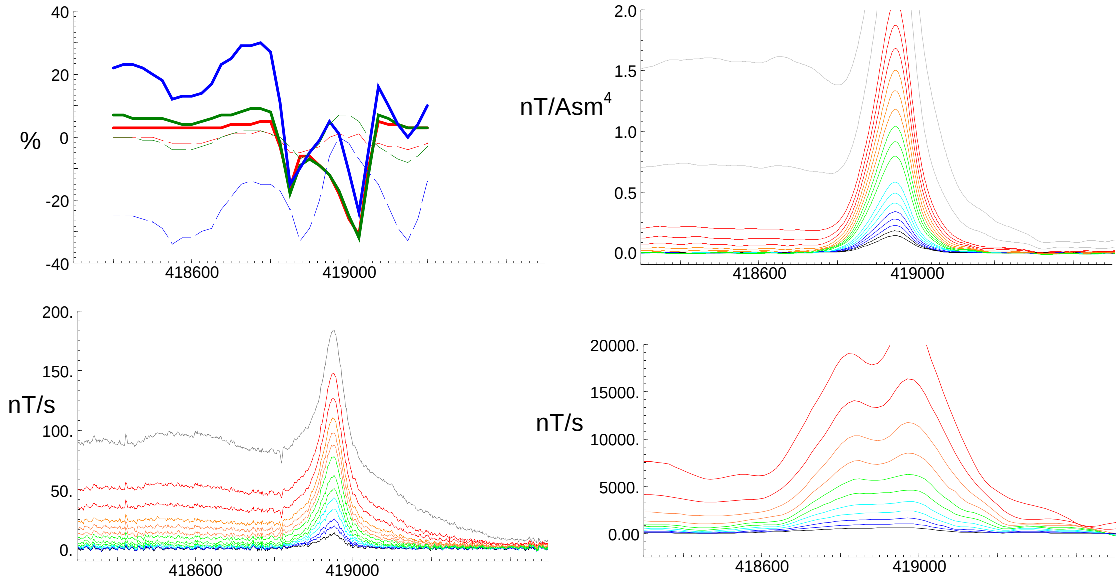

Figure 15: Stacked profiles over the Montcalm deposit, Ontario of a) ground HLEM at 222, 444 and 1777 Hz (200 m coil spacing). Continuous lines are in-phase profiles and dashed lines are quadrature b) VTEM c) AeroTEM II d) MEGATEM II dBz/dt at 30Hz.

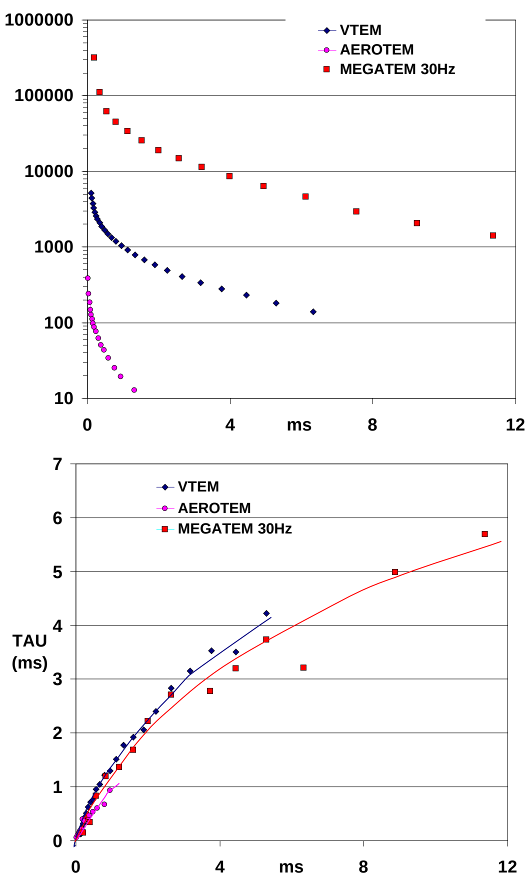

Figure 16: a) Decay curves of the VTEM, AEROTEM and MEGATEM anomalous responses over the Montcalm deposit b) Variation of the time constant with time : running Tau

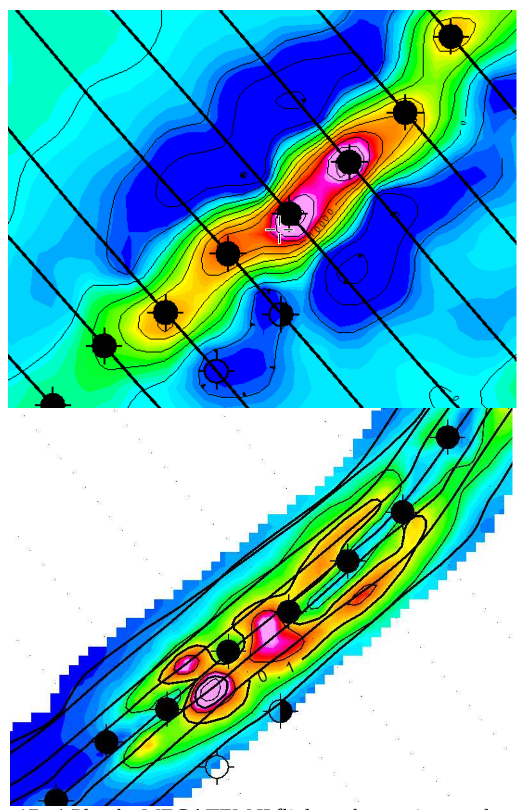

Figure 17: a) Plot the MEGATEM II flight path superimposed on a color map of X component mid off-time channel amplitude. Black dots are the anomaly pick locations b) Plot of a VTEM flight path flown parallel to the same conductor on a colour map of an equivalent off-time window amplitude.

CONCLUSION

Taylor (2005) presented examples of HTEM surveys following-up airborne anomalies as replacement for ground surveys. HTEM survey provided tighter line spacing (50 m vs 200 m), concentric transmitter-loop and receiver coils for good lateral resolution, high density data points (2m) and accurate GPS. All this allowed accurate horizontal position, depth and dip with modelling programs. The targets were drilled and conductors were intersected within 10m of their interpreted positions.

Taylor listed the main advantages of HTEM surveys over ground follow-up:

- Many targets can be covered in a short period of time – 10 per day
- Year-round access and full coverage since open water is not an issue
- Denser data set for modeling
- Topography effects minimized
- Lower cost when several targets have to be followed-up.

Fountain (2005) presented some logistical advantages of the HTEM over the fixed wing systems:

- lower cost on small surveys since the minimum line length is typically 2 or 3 km compared to 8 to 10 km for fixed wing. Mob-demob is also at lower cost
- lower cost on isolated surveys when the ferry distance for fixed-wing systems is large and a camp-based HTEM survey could be flown;
- better terrain contouring in rugged terrain;

Moreover the HTEM data show other advantages such as:

- sharper anomalies with simpler shapes compared to asymmetric anomalies for fixed-wing towed bird systems;
- more accurate positioning of shallow and short conductors;
- better resolution of closely spaced conductors and/or complex strike particularly in areas of cultural interference

Darwin's Theory of Natural Selection dealt with the concept that the evolution of species depended on a number of characteristics required for survival and reproduction and was developed from his observations of finches in the Galapagos. The same evolutionary process of adaptation through mutation for the purpose of survival is true for HTEM systems. The HTEM systems best adapted to their exploration environment and the client's needs will survive. And clients will always need more bandwidth, better resolution and greater depth of penetration at lower cost.

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APPENDIX

AEROTEM

The development of AeroTEM by Aeroquest started in 1996 (Boyko et al, 2001 and Balch et al 2003). A key feature is the rigid, concentric-loop geometry with the receiver coils (Z and X) placed in the center of the transmitter loop. The AeroTEM is the only commercial HTEM system to have this rigid configuration. A second key feature is the transmitting waveform, which is a triangular current pulse. The transmitter current, both on-time and off-time dB/dt full-streamed data are recorded. A bucking coil is used to remove most of the strong primary field of the on-time data. This system design requires that all coils be quite rigid and fixed relative to each other.

In the prototype AeroTEM 1, which made its first production flight in May 1999, transmitter current was 60 A in a transmitting loop of 5 m diameter, for a dipole moment of 18 000 NIA and a bird weight of 270 kg. The base frequency was 150 Hz and the pulse duration was 1.150 ms. The coil assembly, with associated electronics (Figure1), is towed 50 m below the helicopter and nominally 30 m above terrain.

In AeroTEM II (Figure A1), which commenced operations in 2000, dipole moment was raised to 45 000 Am^2. The transmitter loop consists of eight turns of copper wire, 5 m in diameter, with a maximum current of 250 A. Its weight on the helicopter hook is 350 kg.

The AeroTEM III has a 9 m transmitter loop and a dipole moment between 125,000 to 150,000 Am^2 and weighs 700 kg. The system operates at 90 Hz and the triangular pulse is 1.86 ms.

AeroTEM IV offers an increase in signal of three times over AeroTEM III as the dipole moment has increased 400,000 Am^2. The bird operates at a 30 or 90 Hz base frequency. The AeroTEM IV transmitter loop is 12m diameter and the total weight is 630 kg.

Figure A1: The AeroTEM II in flight (courtesy of Aeroquest Ltd).

EXPLORHEM

The geometry of the ExplorHEM system, operated by SpectremAir, is shown in Figure A2. The system represents a helicopter version of the fixed-wing SPECTREM system (Leggatt et al., 2000). The B-field processing of the recorded x, y and z-component data allows for the application of a survey-height correction (Green, 1998). In order to record broad-bandwidth EM data, a 100% duty-cycle square-wave with a RMS dipole moment of 25,600 Am^2 is transmitted at a base frequency of 75 Hz. The bird is constructed from Kevlar nomex in order to minimize weight of the 18m long bird. The transmitter / receiver coil separation is 12 metres.

The broad bandwidth of the data is advantageous for near-surface exploration, such as for kimberlites.

Figure A2: Photograph of the ExplorHEM system

HELIGEOTEM

Fountain et al (2005) described the HeliGEOTEM System of Fugro Airborne Surveys as a system that incorporates the main characteristics of the fixed wing GEOTEM system. The three dB/dt components (x, y, z) are measured continuously in the on-time and off-time allowing the calculation of B field.

The HeliGEOTEM I that was commercially available in 2005 had the following specifications:

- Dipole Moment: 230,000 Am^2
- Waveform Frequency: 30 Hz / 4 ms
- Waveform: Half Sine
- Ttransmitter Loop Diameter: 11 metres, 2 turns
- Transmitter current: 1350A
- Helicopter Hook Weight: 340 kg
- Internal Cabin Rack: 95 kg
- Helicopter MTC: 100 m
- Transmitter Loop MTC: 50 m
- Receiver Bird MTC: 85 m

The HeliGEOTEM II (Figure A3) started operation in 2006 has a larger loop; 14m of four turns with a maximum current of 900 A. The system flies lower, the transmitter loop being at 40 m above ground and the receiver at 78 m.

Figure A3: The HeliGEOTEM II in flight (courtesy of Fugro Airbore Surveys).

HOISTEM

HoisTEM was developed in Australia by Normandy Mining Ltd, now Newmont Mining Inc (Boyd, 2001, 2004). The system was commercialized via a three way joint venture between GPX Airborne Surveys (now known as WorleyParsons-GPX following the merger of GPX with Worley Parsons Limited), Normandy Exploration Ltd. and Geosolutions Pty. Ltd. GPX were to provide the marketing and operation of the system only. Normandy was to provide the hardware; Geosolutions was to provide the software and necessary training. GPX have no access to any of the technology involved in the HoistEM system. Subsequent to commercialisation, 50,000 line km have been surveyed within Australia between years 2002 and 2005 indicating strong industry acceptance.

The 380 kg system contains a 24m-diameter transmitter loop with an inner concentric loop as the receiver coil. It measures the dBz/dt off-time EM response at the centre of the transmitter loop. A 5 ms square-pulse 340 A with a peak dipole moment of 120,000 Am^2 is transmitted at a base frequency of 25 Hz. This pulse has a very rapid switch off of 40 microseconds. In order to power the transmitter a 25 horsepower Kohler petrol motor generator is attached to the skids of the helicopter.

NEWTEM

Newmont Mining Corporation developed a HTEM system during the period 1995 – 2001 (Eaton et al, 2002, 2004). This system was designed primarily for gold exploration in both conductive and resistive environments. The system has some similarities with HoisTEM system since the Normandy's geophysical research group collaborated in some parts of its development. In its current form, the system has been in operation since 1999. The following list highlights some of the NEWTEM system's main features:

- Peak current: 275 amps Loop size: 20 m diameter (80,000 Am^2).
- A precisely-controlled "square wave" current pulse is turned off with a 100-microsecond ramp. The base frequency is 25/30 Hz.
- Measurements from within the pulse out into the "off-time" (10 microseconds to at least 6 milliseconds), sampling at 100 kHz.
- Single or multi-component "in-loop" receiver with motion sensors.
- A noise level in the processed data of about 50 microvolts based on a peak voltage of about 0.5 volts, i.e. 4 decades of signal.
- Overall weight and drag that permit the use of a midsize helicopter.

THEM

THEM Geophysics Inc first started working on development of a towed blimp system in 1998 (Bodger et al. 2005).

Since 2006, they are flying systems called EMOSQUITO (Figure A4). The EMOSQUITO II weights about 200 kg so it can be towed by a small helicopter such as a R44 or a Jet Ranger. The two turn 8 m diameter transmitter loop transmits half-sine, 4 ms pulses (at 30 Hz) with a 200 000 NIA peak moment. Base frequency and pulse width can be adapted to geological problems. Three receiver coils (x, y, z) are located 27 m above the transmitter in quasi coaxial configuration similar to the HeliGEOTEM configuration. The receiver records full waveform data allowing the total B-field calculation.

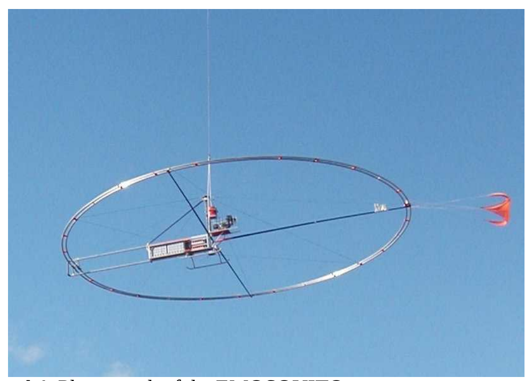

Figure A4: Photograph of the EMOSQUITO

VTEM

The following description of the VTEM (Figure A5) system is taken, with minor modifications and additions, from Witherly et al, 2004 and 2005. The Geotech Ltd. VTEM system entered into commercial service in late 2002 after preliminary work that started in 1998 followed in early 2001 by a major development program. In the early days, the system was tentatively named Dream Catcher and then Scorpion but at the end Versatile EM or VTEM was better accepted by the exploration community. Commonly, the VTEM system uses the co-incident loop geometry including a transmitter loop of 26 m in diameter, a bucking coil of 3.3 m (a 2006 addition for the B-field measurement) and a 1.1 m diameter receiver coil situated in the center. Currently, only a vertical axis receiver coil (recording Z-component data) is employed. In-flight, only a modest amount of forward speed is needed to have the main loop assume a horizontal angle, with an angle of deployment of approximately 28º from vertical behind the helicopter.

The transmitter loop is made up of over 48 separate pieces each less than 2 m in length (to facilitate shipping) that are field assembled by simply joining pieces via a tapered end design. The transmitter cables are then fed through the tube structure. The entire assembly (transmitter loop, bulking coil and receiver coil) are held together by a network of cables that provides the tension to hold the structure together. The whole process of assembling and installation, including the helicopter wiring, takes up to two days.

To date, the preferred base frequency has been 25/30 Hz with a 40% duty cycle. This has meant a primary pulse width of approximately 8 ms and sampling time of approximately 7.5 ms. The system was designed to support basically any waveform shape with a base frequency up to 200 Hz. A single turn transmitter loop has been used for shallow mapping applications. With this configuration, a faster current shut-off is possible, thereby exciting higher frequencies. This configuration was used for a series of surveys for kimberlite exploration in the Canadian Arctic.

Power for the system is drawn off the helicopter alternator, either via a direct tap on the helicopter's 28 V supply or more recently via an electronic inverter. The Mk II system that has been in operation since mid-2003 has a dipole moment of ~425,000 NIA up to 600000 NIA but at a reduced duty cycle, i.e. shorter pulse length.

Figure A5: The VTEM sytem in flight (courtesy of Geotech)

SKYTEM

SkyTEM was designed for hydrogeophysical and environmental investigations (Sørensen and Auken, 2004) and developed as an alternative to ground-based TEM surveying. The SkyTEM system is operated in North and South-America by NOVATEM.

Independent of the helicopter, the entire system is carried as an external sling load as shown in FigureA6. No personnel is required on board the helicopter to operate the equipment. Not having an operator in the helicopter reduces the total weight to about 280 kg.

The transmitter power is drawn off a motor generator for about 2 hours of operation. A current of 30 A for the low moment system or up to 100A for the high moment system is passed in 4 or 5 turns of a 494.4 m^2 octagonal loop. A larger 7 turn loop providing a 550 000 Am^2 dipole moment has been tested successfully. The base frequency could be selected between 25 Hz or 30 Hz.

The total field magnetic sensor is located few meters above the transmitter loop and measurements are synchronized during the transmitter off-time allowing good quality data. Elevation is measured using two laser altimeters mounted on the transmitter frame, measuring the height 20 times per second. Inclinometers are mounted in both the x and y directions. Transmitter waveform information (current, turn-on and turn-off ramp times) and other controlling parameters of the measuring process are recorded during surveys ensuring high data-quality control.

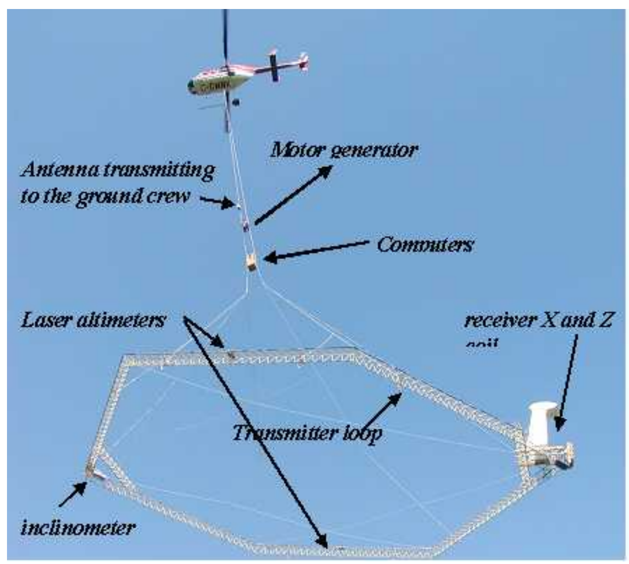

Figure A6: Details of the SKYTEM system components (courtesy of SkyTEM ApS)