Paper 13

Advances in Ground and Borehole EM Survey Technology to 2017

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ABSTRACT

Development of transient electromagnetic (TEM) systems, surface and borehole, from the last decade are discussed with references to important features which are enhancing their performance. Transmitters, sensors and receiver systems are covered in separate sections in addition to borehole-specific technology. The general trends towards lower frequency and higher transmitter current are discussed. The relationship between highly-conductive TEM targets and TEM system design is discussed with some model examples used to illustrate the issues at play. Examples of recent discoveries and recent TEM examples of interest are presented.

INTRODUCTION

It is fair to say that electromagnetic (EM) methods, particularly transient electromagnetic (TEM) methods, to probe the presence and distribution of deep electrically-conductive mineral targets, have become a very important and commonplace part of the exploration programs for base metals and other conductive targets. Explorers for conductive mineral deposits, particularly massive sulphide deposits can only ignore the value of TEM surveys at their own peril.

In the last decade, significant discoveries of base metal deposits have been directly attributed to the use of TEM geophysics, especially borehole TEM surveying. Examples of recent discoveries are presented and discussed during this paper. During this decade, our industry continued to develop new instrumentation, new surveying techniques, new processing and interpretation methodologies and new approaches to the problem of detecting deep conductive bodies with no surface expression.

Transient electromagnetic geophysics continues to be undertaken at lower transmitter frequencies. These changes are being driven by the desire for better discrimination of good conductors from weaker ones and by the need to penetrate deeply into weathered terrain. They are facilitated by improvements to the technology that is used to collect and process TEM data. TEM surveys are being carried out at frequencies often as low as 0.1 Hz. Some transmitter systems are capable of transmitting several hundred amps, a considerable increase over the decade before.

The following four sections of this paper discuss four areas of technology in EM systems: the transmitter, the sensors, the receiver and borehole systems.

Exploration for highly-conductive nickel sulphide targets has continued to drive some aspects of TEM system development and, for this reason, a model study of highly-conductive targets is included in this paper.

Four exploration examples are presented towards the end of this paper. Exploration at these locations relies on TEM for delineation and discovery of their metal resources.

It is clear that TEM technology will continue to evolve and participate in discovery of more difficult orebodies. Part of this evolution may be the development of distributed TEM systems to increase the data density and reduce the noise in TEM surveys.

TRANSMITTER SYSTEMS

As discussed in a presentation (Lamontagne, 2007) at Exploration '07, there has been a trend towards the development and use of higher-powered EM transmitters in our industry. Naturally this trend has been tempered by issues of portability and access, but during this decade we have seen TEM surveys in exploration scenarios regularly employing transmitter currents in excess of 100 A. Examples of innovation in transmitter system development are presented here.

Gap GeoPak (Adelaide, Australia) developed a 70 kW transmitter for loop and grounded dipole loads named the HPTX-70. This transmitter has a maximum current of 350 A, a maximum voltage of 1200 V and a maximum instantaneous power of 70 kW. Figure 1 shows the HPTX-70 transmitter, which was first deployed commercially in 2009. The diesel engine, generator and electronics are incorporated into a dual-axle trailer. This system includes remote monitoring of transmitter/generator performance and remote start/stop capabilities. Gap GeoPak have also developed smaller, more portable transmitter systems with lower power, (with maximum current up to 200 A) specifically for smaller transmitter loops (such as 100 m square) with heavy gauge loop wire, used in TEM surveys for mineral exploration or UXO applications. In standard practice, copper wire of 35 square mm section is used with the HPTX-70 for TEM surveys, usually with a single turn loop. The HPTX-70 typically achieves 200–240 A for 400–500 m loop sides, 160–200 A for 800 m loop sides and 140 A for 1 km loop sides (M. Cattach, pers. comm.).

In "Proceedings of Exploration 17: Sixth Decennial International Conference on Mineral Exploration" edited by V. Tschirhart and M.D. Thomas, 2017, p. 169–182

Figure 1: Gap Geopak HPTX-70 transmitter system.

Lamontagne Geophysics (Kingston, Canada) has developed a new transmitter for their UTEM 5 system (Figure 2). It represents an advance in flexibility and stability over previous generations. It is capable of operating over output power ranges from 2.5 kW to 12 kW with dynamic current waveform regulation to 0.01% (Y. Lamontagne, pers. comm.). UTEM transmitters are always operated at 100% duty cycle, without off-time. UTEM systems are most often used with transmitter loops of dimension 1500 m or more. The UTEM 5 transmitter is commonly used at a 10 kW level. At this level, 9 A RMS can be transmitted into a square loop with 2000 m side length using standard UTEM copper wire (14 gauge) of 9 ohm/km resistance. A loop with side length 1000 m could be used with up to 18 A RMS current.

Abitibi Geophysics (Val-d'Or, Canada) developed a commercial TEM transmitter system, TerraScope, in 2009. It is capable of a maximum current of 40 A and maximum output power of approximately 15 kW.

Monex Geoscope (Melbourne, Australia) developed a portable 50 A TEM transmitter, Terra TX-50, in 2009. This transmitter is powered by generator and voltage rectifier or batteries and can output a maximum of 250 V at 6 kW. There is emphasis on stable, fast turn-off with this transmitter (e.g. 40 microseconds at 50 A into a 50 m x 50 m loop).

Electromagnetic Imaging Technology (Perth, Australia) developed a transmitter system, SMARTx4, in 2015, with maximum current 40 A and maximum output power 3.6 kW. This transmitter incorporates tightly-regulated DC generation, GPS synchronization, automatic damping, an environmentally sealed enclosure, in-built 24-bit digitization of current waveform and operating temperatures from -40° C to +50° C.

Transmitter systems, and indeed other survey hardware components, tend to be manufactured by a mixture of service companies and instrumentation companies. Very few end-users or explorers make their own EM equipment. In the case of transmitters, one exception is IGO (Western Australia, Australia), who designed a high power, high current transmitter system especially for deep borehole EM work at their Kambalda Long Nickel Mine.

Figure 2: UTEM 5 transmitter system, Lamontagne Geophysics Limited.

A reasonable number of transmitter manufacturers now produce equipment that incorporates a GPS-time-synchronization function, or an add-on to achieve that. Where the terrain and access allows, there has been a trend towards the use of larger diameter loop wire, to facilitate the use of higher currents. This, in turn, has created a need for more robust tools for deploying, retrieving and storing wire.

An innovative feature introduced in UTEM systems was the ability to operate multiple transmitters simultaneously in close proximity at slightly different (closely-spaced) frequencies that can be separated by the receiver. This was first introduced into commercial surveys in 2012 (Y. Lamontagne, pers. comm.). This functionality allows the data from multiple loops to be collected simultaneously, with the advantage of significantly decreasing the time taken to do a multiple transmitter loop TEM survey, either surface or borehole.

This functionality was introduced into the Electromagnetic Imaging Technology receiver systems (SMARTem24 and DigiAtlantis) and transmitter control systems in 2015 (Duncan and Dueck, 2015). The main innovation here is the ability to stack well enough to attenuate nearby transmitter frequencies. SJ Geophysics has also used measurements taken while multiple transmitters are operating at different frequencies in close proximity (S. Visser, pers. comm.).

A further transmitter-related development was introduced by Electromagnetic Imaging Technology in 2015—an output multiplexer (really a de-multiplexer) which can automatically swap the output of a single transmitter out onto any of four or more loops in a given controlled sequence, usually every minute or two depending on time required for each reading. This instrument has been tested with a range of commercial transmitter systems (including Zonge, Geonics, Phoenix, Crone and Gap Geophysics) and can currently handle currents up to 100 A and voltages up to 1000 V. Loops are swapped by the multiplexer under the control of a device which is responsible for the timing of the transmitter switching. The active loop is only swapped when transmitters are disabled by the controller. Receiver measurements are automatically synchronized with the pattern of loop swapping. The result is a potential considerable time-saving in a survey using multiple loops and a single transmitter. Only one occupation of each station is required to collect data from all loops deployed; the loop swapping and data collection is automated so that only one key press is required by the receiver operator to initiate a full sequence of measurements.

Some transmitter systems are for sale to service providers, others are developed by service providers and not available to other users. Manufacturers offering TEM transmitters for sale include Zonge, Phoenix Geophysics, Geonics, Electromagnetic Imaging Technology, Monex Geoscope, Tsikl, and ZaVet.

SENSORS

EM sensors continue to evolve in response to the exploration industry's demands for higher performance. One particularly significant driver has been the desire to push lower the frequencies of TEM measurements and this has been the case for more than a decade now (Lamontagne, 2007; Duncan et al, 2007; King, 2007).

Magnetic field sensor architectures can be broadly classified into three groups: i) coils, ii) feedback coils and other 'inductive magnetometers' and iii) magnetometers. A comprehensive summary of magnetic field sensing technologies, with a focus on inductive magnetometers, is included in Macnae and Hennessy (2017, this volume). The magnetometer group can be further divided into a number of technologies used for TEM measurements including the fluxgate, SQUID and less common atomic architectures.

Liquid nitrogen-cooled SQUID magnetometers developed by IPHT (Institut fur Photonische Technologien, 'Jessy DEEP', Germany) and CSIRO ('LANDTEM', Australia) were developed mostly in the previous decade and have continued to be used on commercial surveys during this decade. Both can be paired with any compatible data acquisition system and transmitter system. IPHT also manufacture a liquid helium-cooled SQUID, shown in Figure 3 with its control unit. CSIRO developed a prototype liquid helium-cooled SQUID in conjunction with BHP Billiton in the past decade; this is not currently in commercial usage. During this decade, the main improvements with the IPHT SQUIDs have been with the sensitivity and the tolerance to high slew rates. Additionally, the holding time of the helium cryostat has been extended from 203 days to 7 days. JOGMEC (Japan Oil, Gas and Metals National Corporation) has developed a SQUID-based geophysical data collection system called SQUITEM (http://www.jogmec.go.jp/english/stockpiling/metal_10_000002.html). The sensor is available for in-house data collection projects and to joint venture partners.

Figure 3: Jessy Deep low-temperature 3-component SQUID sensor system (IPHT/Supracon).

Surveys with SQUID sensors are more often than not carried out at relatively low transmitter frequencies (say less than 5 Hz) in order to exploit the low intrinsic noise level of these sensors at low frequency (see Macnae and Hennessy, 2017). SQUIDs do require some extra effort to use (including provision of liquid nitrogen or helium as required) and some effort must be made to ensure the sensor is isolated from motion to allow low noise performance to be used effectively. Macnae and Hennessy (2017) assert that background atmospheric noise can result in data from SQUID systems to be of similar quality to that from other sensor types with higher intrinsic noise floor.

The use of fluxgate magnetometers in EM geophysics has continued to increase in this decade. A number of fluxgate magnetometer manufacturers develop products marketed at geophysics usage, including Bartington Instruments UK, who seem to have the most popular low-noise 3-component fluxgate sensors used for commercial TEM surveys. Fluxgate magnetometer sensors are small and have relatively low power consumption. The instruments with lowest noise at low TEM frequencies tend not to have a particularly wide bandwidth. The bandwidth of low-noise Bartington 3-component sensors is approximately 3 kHz but bandwidth can be increased at the expense of additional noise. An entire 3-component sensor and supporting electronics can be incorporated in a volume of a few tens of cubic centimeters. As a result, they are convenient to use in borehole EM applications. Historically, fluxgate magnetometers were used mainly in geomagnetic and magneto-telluric geophysical applications because of their low signal-to-noise at low frequencies (less than say 1 Hz). However, from 1998, fluxgates started to become popular in mainstream exploration geophysics TEM systems, especially in conductive terrain where low transmitter frequencies were employed. Fluxgate magnetometers do not have the low instrument noise levels of SQUID sensors across the geophysical spectrum, nor the bandwidth, but have become popular because they are small, simple to use and perform well at low frequencies.

There are reports of promising investigations into lower-noise fluxgate magnetometer systems, but, in general, the intrinsic noise level of fluxgate sensor systems used in mainstream commercial TEM geophysical surveys has not changed much since they started to become popular. The best sensors have a noise level of roughly 5 pT per root Hz at 1 Hz.

'Atomic' magnetometers, utilizing the magnetic resonance behavior of alkali vapor atoms, are mostly used in geomagnetic measurements. In the last decade, they have been used increasingly in TEM surveys. Almost all commercial magnetometers in this class generate a scalar measurement of magnetic field, not a vector magnetic field component. Measurements are thus independent of sensor alignment in general, although 'heading error' for most of these sensors can be significant. At 1 Hz, a commercial cesium vapor magnetometer can have a noise level roughly 10 times lower than a good fluxgate magnetometer. At even lower frequencies, commercial atomic magnetometers perform well in TEM surveys. Cesium vapor magnetometers have been, and continue to be, used extensively in low frequency (typically 0.1 Hz) TEM surveys (Duncan et al, 2007).

Figure 4: Cesium vapor magnetometer interfaced to a Gap Geophysics frequency counter and data logger system.

Atomic magnetometers theoretically have a bandwidth up to their larmor frequency (typically hundreds of kHz) but in practice measurements are limited in bandwidth by the circuitry used to measure the larmor frequency. At frequencies above several tens of Hz, atomic magnetometers have signal-to-noise which cannot compete with other sensors such as SQUIDs and inductive magnetometers. Gap Geophysics have developed frequency-counter systems that accurately sample the larmor frequency of a cesium vapor magnetometer sensor, at sample rates up to 9600 samples per second. An atomic magnetometer sensor, mounted on tripod and interfaced to a Gap Geophysics data acquisition system in a TEM survey, is illustrated in Figure 4.

'Inductive magnetometers' use a coil detector, usually with a permeable core material, in conjunction with electronics to generate a low-noise signal that is proportional to magnetic field (not dB/dt) over some part of the EM geophysical spectrum. Below this range, usually these sensors behave like a coil with output proportional to the time-derivative of the sensed magnetic field. Traditionally, this style of sensor has been used in magnetotelluric (MT) and controlled-source audio-frequency magnetotelluric (CSAMT) magnetic field measurements. However, some commercial TEM systems such as UTEM use inductive magnetometers and have done so for several decades. Figure 5 shows the UTEM 5 3-component surface coil which incorporates a sampling system and fibre-optic interface to a UTEM 5 receiver system.

Figure 5: UTEM 5 3-component inductive magnetometer sensor (Lamontagne Geophysics Ltd.).

Inductive magnetometers are likewise used in some TEM surveys carried out by SJ Geophysics (Vancouver, Canada). Abitibi Geophysics (Val-d'Or, Canada), in conjunction with Professor James Macnae of RMIT (Melbourne, Australia) have developed 'ARMIT' (Macnae, 2012), a variety of inductive magnetometers with a novel architecture which results in a fairly compact and mechanically robust sensor. ARMIT 3-component sensors include orientation sensors to facilitate levelling corrections. Vale Canada Ltd, a subsidiary of Brazilian mining company Vale, has recently developed a TEM system mainly using inductive magnetometers (B. Polzer, pers. comm.).

Intrinsic noise levels of inductive magnetometers tend to be impressively low across a wide range of frequencies. However, the use of inductive magnetometers in TEM surveys, especially low frequency TEM surveys, requires that an accurate calibration of sensors to be carried out (possibly during a survey) in order to remove, via deconvolution, effects of the sensor's architecture. Behavior of virtually all members of this class of sensor is similar to that of a single-pole high-pass-filtered (AC-coupled) magnetometer. When surveys are carried out in the vicinity of the high-pass corner frequency of the sensor, the understanding of the sensor's behavior becomes critical.

Measuring or deriving a 'B-field' response has continued to become more popular in the application of detecting a conductive target, especially when it is in the presence of other, weaker, host or stratigraphic conductors—a common occurrence. There has been considerably more interest, in the last decade, in sensors that produce a magnetic field measurement than those producing a magnetic field time-derivative.

In May, 2011, a controlled test of some modern EM sensor intrinsic noise levels was carried out in Utah, USA (J. Kingman, pers. comm.). This was a repeat of a similar experiment carried out in 1984 by Frank Morrison and his colleagues from University of California, Berkeley. The results of the 2011 tests are not yet fully publically available.

RECEIVER SYSTEMS

Geophysical equipment continues to benefit from the improvement in computing capacity and related advances in electronics seen in consumer devices. New receiver systems, with modern electronic components, displays, storage, battery technologies and operating system software have been developed in the preceding decade. The main functions of a TEM receiver system are timing synchronization, amplification, digitization, stacking, other processing, time-windowing, storage and display. A good understanding of signal processing is important for the design of core parts of the receiver's software.

Properly-designed stacking and windowing functions make a significant difference to the performance of receiver systems, especially in the presence of interference from nearby electrical infrastructure, from very low frequency electromagnetics (VLF) and lower frequency radio transmissions and from low frequency noise caused by sensor motion, tellurics and vehicle traffic. Without a good stacking algorithm, it is impossible to achieve good results from a TEM survey being operated near another survey at a different frequency. With appropriate stacking, surveys at closely-spaced frequencies can be carried out in close proximity (refer to 'Transmitter Systems' above). In the following, I'll outline some of the innovative instruments that have been deployed for the first time in the preceding decade.

In 2010, the first version of general purpose 24-bit, 16-channel SMARTem24 time-series receivers incorporating a ruggedized PC were released by Electromagnetic Imaging Technology (Figure 6). Following on from previous SMARTem systems, this receiver is designed to record/process full time-series and to work with a large range of sensors and transmitters. The receiver unit is GPS-synchronized with a transmitter controller instrument. Sample rates, amplification, processing options, transmitter frequencies and display options are all accessed via a Windows GUI on an integrated rugged PC. SMARTem24 receiver systems are used in TEM, magnetometric resistivity (MMR) and induced polarization (IP) surveys.

Figure 6: SMARTem24 receiver system (Electromagnetic Imaging Technology).

Figure 7: UTEM 5 receiver system (Lamontagne Geophysics Ltd.).

In 2011, Lamontagne Geophysics trialed the UTEM 5 receiver, sensor and transmitter system for surface and borehole TEM surveys and induced source resistivity (ISR) surveys. The UTEM 5 sensors and transmitters result in a more sensitive system than earlier UTEM systems. The receiver itself (Figure 7) has a number of new acquisition and processing features including multiple interleaved frequency stacking, a bi-directional fibre-optic sensor interface, options for stacking and windowing weights, scope waveform viewing and time-series data acquisition (Y. Lamontagne, pers. comm.). UTEM 5 systems are used in-house by Lamontagne Geophysics survey crews.

During the last decade, Vale initially developed, then improved a receiver system for surface and borehole surveys for their in-house use. The focus for this system is the collection of time-series TEM data which is processed on a PC sometime after being recorded.

Some manufacturers have developed, or are developing, 'distributed' receiver instrumentation that may have application in EM surveys. The focus for most developers of distributed instrumentation in the electrical geophysics space has been IP, resistivity and MT measurements. Most of these systems do not have fast enough sampling for routine TEM measurements. SJ Geophysics has developed a distributed data logger system, called Volterra, capable of recording TEM data at surface and in a borehole in addition to IP and MT data. Volterra receiver units (Figure 8) are quite small, containing 24-bit digitization, memory for full waveform recording and GPS timing. They are cylindrical so that they can be used for borehole TEM surveying. In TEM surveys, Volterra receivers are interfaced with inductive magnetometers or fluxgate magnetometers.

Figure 8: Volterra receiver (SJ Geophysics Limited).

Distributed data acquisition hardware, used in TEM surveys, can offer some potentially significant advantages in data density, redundancy, speed, noise reduction and general survey efficiency, especially on large surveys. One of the main requirements for achieving a scaling up of distributed TEM surveys is the availability of inexpensive sensors with reasonable performance. This problem has not been solved.

BOREHOLE TEM SYSTEMS

UTEM 4 (Lamontagne Geophysics) continues to be an innovative platform for the collection of borehole TEM data. First developed in the mid-1990s, it continues to be a popular system, especially in the exploration for highly-conductive targets such as those in nickel exploration camps like Sudbury and Raglan, Canada. Systems are operated by Lamontagne Geophysics crews. The UTEM 4 borehole sensors are 3-component inductive magnetometers and sampled responses are transmitted digitally to the surface via a fibre-optic element in the logging cable at up to 100,000 samples per second per component. UTEM surveys are carried out at 100% duty cycle. Advances in the system electronics and processing software have taken place in the preceding decade.

In 2009, Electromagnetic Imaging Technology's DigiAtlantis borehole EM system was first used. DigiAtlantis consists of a 3-component fluxgate magnetometer sensor, in a 33 mm diameter tool, with digital transmission of raw sampled data (at sample rates up to 25,000 samples per second per component) to the surface over copper wires in standard copper-wire logging cables. This was the result of evolution of an analog version of this system, first used in 2004. DigiAtlantis data collection is GPS-synchronized to a range of transmitter systems. A typical display that would be used by an operator of this system is shown in Figure 9. DigiAtlantis is used in borehole TEM and MMR surveys. MMR surveys are generally done at low frequency and the low-noise fluxgate sensor is a good option for that.

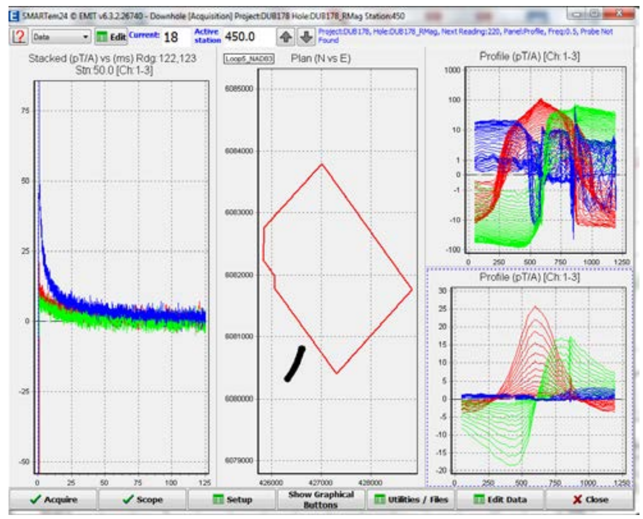

Figure 9: DigiAtlantis operator GUI (Electromagnetic Imaging Technology).

SJ Geophysics use their Volterra system for borehole TEM applications, also using a low-noise 3-component fluxgate magnetometer. Data can be autonomously recorded within the Volterra receiver unit in the hole, allowing the sensor and other electronics to be suspended below the drill bit, with measurements made while drill rods are removed. This method of logging means no conventional logging cable is required.

In the last decade, Vale Canada has developed a borehole TEM system used in-house alongside their surface TEM system (Ben Polzer, pers.comm.). This system uses either 3-component fluxgate magnetometer sensors or induction magnetometers and is operated as an autonomous system, recording raw time-series internally with no data coming to surface in real-time and no need for a conventional logging cable. A Kevlar string can be used to suspend the system in the hole.

HIGHLY-CONDUCTIVE TARGETS

The problem of exploring for highly-conductive targets, such as significant nickel sulphide deposits, has continued to drive some aspects of technology development in TEM surveys. Thus, it is worth discussing these targets here in the context of modern TEM surveys and instrumentation. In particular, it is timely to review the response of highly-conductive targets in the context of the considerably lower frequencies being used commonly nowadays in TEM surveys and the increasing use of magnetometer sensors at both 50% and 100% transmitter duty cycle.

In the context of modern EM exploration surveys, I am going to define highly-conductive targets as being reasonably large (perhaps 200 m or more in at least two dimensions) and having a conductivity-thickness product (conductance) of 50,000 S or higher. One of the most-commonly referenced yet extreme targets in this category is the Ovoid at Voisey's Bay (Labrador, Canada) which has a conductance estimated to be as high as 10,000,000 S (A. King, pers. comm.). Only species of pyrrhotite and nickel and copper sulphide minerals can cause one of these highly-conductive mineral deposits in nature, and they need to be present in extremely high percentages to achieve that. The targets we discuss here would be principally from the magmatic nickel-copper deposit family. We can almost categorically rule volcanogenic massive sulphide (VMS) deposits out of this category due to the presence of other minerals of much lower electrical conductivity.

The reason that a highly-conductive target is difficult to detect with TEM is that EM responses from it are mostly in-phase with the transmitter current (and thus the target response is difficult to separate from that of the transmitter loop).

The results of a simple modelling study to illustrate the problems of detection of some highly-conductive targets will be presented here. The modelling approach here is one first outlined by Kaufman (1978) and was used to create a simple, yet accurate modelling scheme restricted to a survey (transmitter loop and target) with axial symmetry. Targets are modelled with finite thickness, not as infinitely thin sheets—this allows simulation of currents flowing in only a fraction of the conductor thickness—indeed the case with high conductivity TEM targets. Targets are modelled as non-magnetic.

The model code use here was developed in MATLAB and tested against analytic models for the TEM response of a sphere, which is another class of model that can be computed with this code. Discretization of the model scheme was made finer until it no longer had any impact on results and the results are believed to be accurate. Figure 10 illustrates the geometry of the model used here. It simulates the response of a highly-conductive disc (cylindrical slab or disc with finite thickness) in a borehole TEM survey. The model was used to simulate the borehole TEM response of a 400 m diameter conductive horizontal disc centered at a depth of 1000 m, with a circular transmitter loop of diameter 1000 m at the surface. A transmitter current of 20 A was used in the model calculations, with waveforms of 50% and 100% duty cycle. Clearly, model results could be scaled up/down with higher or lower transmitter currents respectively.

A range of target thickness and conductivity were modelled. Responses were calculated for several TEM transmitter frequencies, 0.1 Hz, 1 Hz and 10 Hz, to span the range of frequencies that might be used in this application currently and in the recent past. Time windows used modelled are a roughly logarithmic progression of 20 windows spanning the available time.

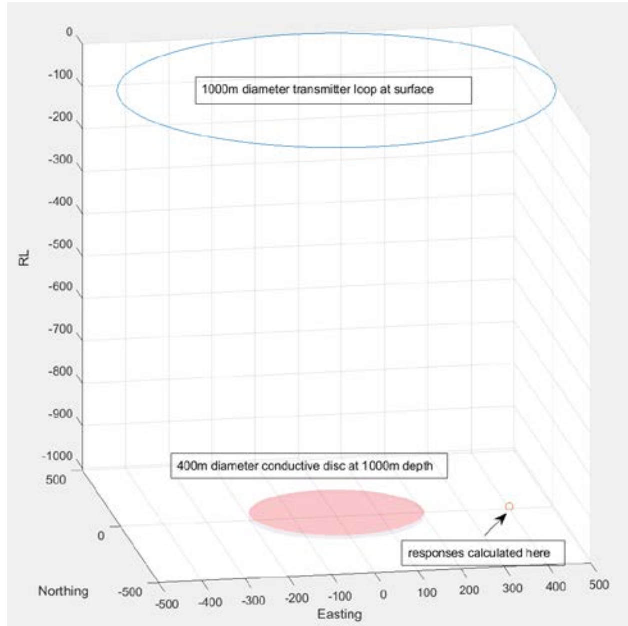

Figure 10: Geometry of the model used to simulate the borehole TEM response of highly-conductive targets. The model has a 1000 m diameter circular transmitter loop carrying 20 A current and a 400 m diameter conductive disc at a depth of 1000 m.

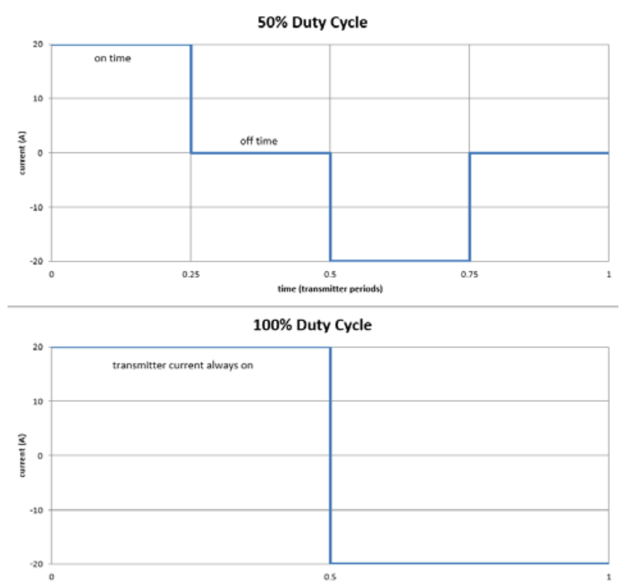

Figure 11: Transmitter waveforms used in model calculations.

Results are presented here for 50% and 100% duty cycle transmitter waveforms illustrated in Figure 11. Four types of results for each model are presented here. For a 50% duty cycle transmitter waveform, the B response in the off-time is computed, as is the B response in the on-time. For 100% duty cycle, the B response is computed, along with the 'late-time-normalized' version of that, in which all time windows prior to the last window have the response measured at the last window subtracted from them (and the latest window is not plotted, since it is already present in the on-time plots). Late-time-normalization is a common treatment for on-time magnetic field presentation in order to remove an estimate of primary field. No dB/dt responses are considered here. They are rather small in these cases, aside from during the switching of the transmitter.

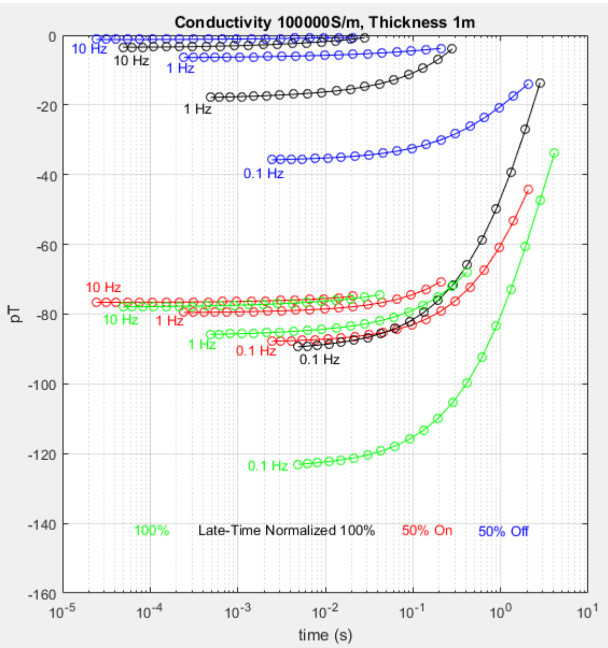

Figure 12: Decays calculated for a conductive disc of diameter 400 m, thickness 1 m and conductivity 100,000 S/m.

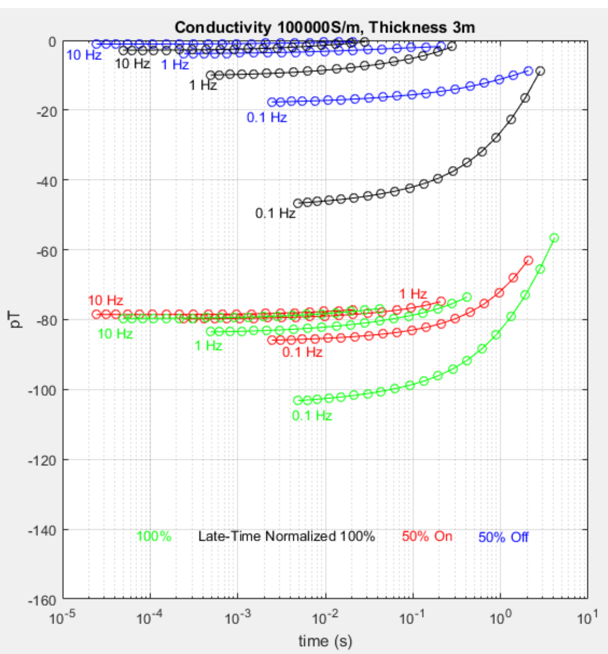

Figure 13: Decays calculated for a conductive disc of diameter 400 m, thickness 3 m and conductivity 100,000 S/m.

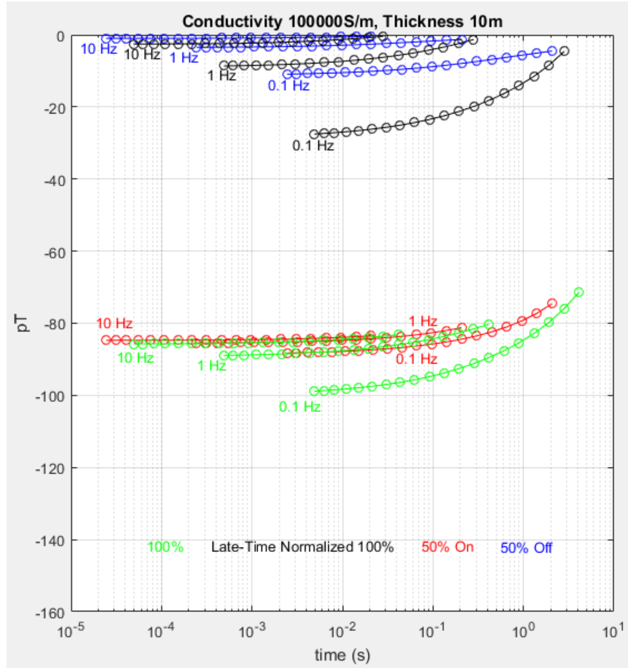

Figure 14: Decays calculated for a conductive disc of diameter 400 m, thickness 10 m and conductivity 100,000 S/m.

A range of conductors at the extreme end of the conductivity spectrum (100,000 S/m) are modelled with results presented in Figures 12–14 for various thicknesses: 1 m thick in Figure 12, 3 m thick in Figure 13 and 10 m thick in Figure 14. Conductance of these targets is 100,000 S, 300,000 S and, 1,000,000 S respectively. The plots show modelled vertical component decays (response versus log time) from a depth of 1000 m (as shown in Figure 10, to simulate observations in a borehole near the conductor) and all are plotted at the same scales for comparison. Values are negative following the convention of a negative off-hole response. Responses shown in all plots are 100% duty cycle B in green, late-time normalized 100% duty cycle B in black, 50% duty cycle on-time B in red and 50% duty cycle off-time B in blue.

The response of the targets illustrated in Figures 12–14 is larger at lower transmitter frequencies. The increase in response with decreasing transmitter frequency is most marked with the off-time B-field data and the late-time normalized 100% duty cycle B-field data. The 0.1 Hz response from the 1,000,000 S target illustrated in Figure 14, at a time equivalent to the last window of the 1 Hz decay, is six times larger than the response at 1 Hz for the off-time model (blue curves) and 15 times larger for the late-time normalized 100% duty cycle model (black curves). This is a significant enhancement of signal, at an equivalent delay time, simply as a result of transmitting at a lower frequency. Similar enhancements are seen for the thinner targets in Figures 12 and 13.

It is clear from the progression of responses illustrated in Figures 12–14 that the on-time responses (50% and 100% duty cycle, red and green curves) behave in one manner and the off-time B response and late-time-normalized on-time responses (blue and black curves) behave in another manner, as the highly-conductive target becomes thicker. However, off-time responses do not head to zero with high conductance in the manner that is suggested by a simplistic analysis of high-conductance behavior.

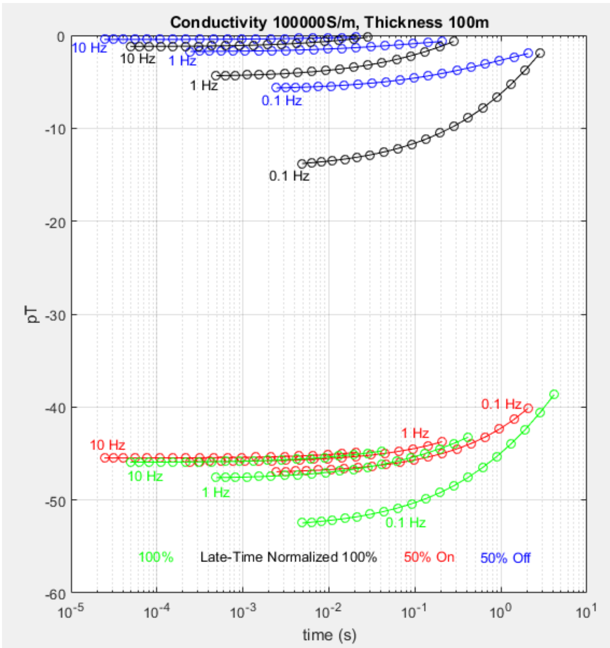

Figure 15: Decays calculated for a conductive disc of diameter 200 m, thickness 100 m and conductivity 100,000 S/m. This model is designed to simulate the response of a conductor similar to the Ovoid.

In Figures 12–14, the late-time normalized 100% duty cycle responses (black curves) are roughly double the off-time responses (blue curves) at early times for all transmitter frequencies and all models. At late time, the late-time normalized 100% duty cycle model responses are roughly the same as the late-time 50% duty cycle off-time models.

For highly-conductive targets, the on-time response at 50% duty cycle and 100% duty cycle is rather similar in amplitude. This is a result of the switch-on at 50% adding constructively to the previous switch-off and delivering a response similar to that from the double amplitude switch at 100%.

Reviewing the B responses for the thick conductive target in Figure 14 we can say that at 0.1 Hz, it would be difficult to classify the response as 'non-decaying' (a description used to suggest completely in-phase secondary field behavior). This observation is much more likely to be made at 1 Hz and far more likely again at 10 Hz. For the responses from the thinner targets in Figures 12 and 13, only the 10 Hz model responses show little sign of decay. At these frequencies, the responses observed in off-time and in late-time normalized 100% duty cycle approach zero.

It should be emphasized that targets like those modelled here do exist in nature but also that they are at the extreme end of the spectrum in terms of conductivity (and thus EM behavior). These are difficult targets for EM surveys for the reasons discussed above, especially when they have no halo or associated zone of weaker conductivity. Targets such as these have driven the development of TEM systems measuring in-phase with the primary field, the best known of which is UTEM (West et al, 1984).

For the purposes of comparison with the model responses in Figures 12–14, a thicker target is simulated. In Figure 15, the response of a target similar to the Voisey's Bay Ovoid nickel/copper deposit is presented (buried to the same depth as the previous targets). The Ovoid has an estimated conductivity of 100,000 S/m, an average thickness of 100 m (conductance 10,000,000 S) and an average diameter of roughly 200 m (A. King, pers. comm.). This is half the diameter of the targets modelled in Figures 12–14. King (2007) has an excellent summary of this deposit, discovered in 1994. In order to calculate responses at the same distance from the target (200 m) as before, the measurement point for the model responses is moved 100 m closer to the axis of the model (refer to Figure 10). The decay rates and ratio of on-time to off-time responses are not dissimilar to those from the larger 1,000,000 S target in Figure 14, even though the Ovoid target is ten times thicker.

Figure 16 illustrates the current flowing in the Ovoid model at the latest time in a 100% duty cycle survey at a transmitter frequency of 0.1 Hz. Thus, this snapshot is 5 seconds after the transmitter current step. This plot illustrates the eddy current flowing in/out of the page in a vertical slice through the centre of the disc. The red colors show the highest currents. It is clear that most current flows only in the outer shell of the conductor, even at this long delay. In fact most flows along the top and bottom rim of the disc. That is the part of the conductor that is easiest to see with TEM. As with the 1,000,000 S target (Figure 14), it would be hard to consider the response in Figure 15 to be non-decaying at 0.1 Hz.

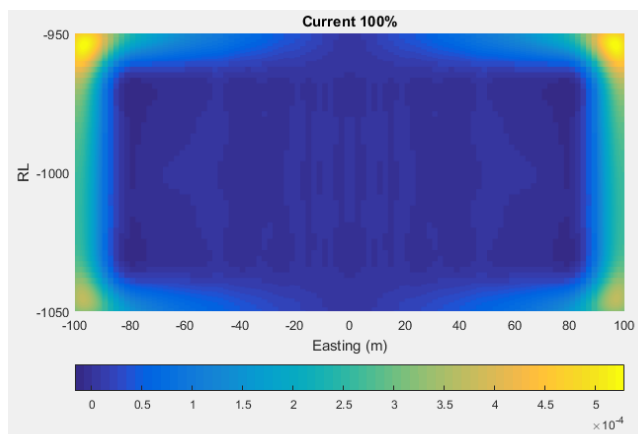

Figure 16: An image of the eddy currents flowing in a 100 m thick conductor (conductivity 100,000 S/m) at the latest time delay in a 100% duty cycle TEM survey at 0.1 Hz.

Simple rules (for example, in Gallagher et al, 1985) tell us that the 'late-time decay constant' for this target is very large—of the order of two hundred seconds. However, Gallagher et al (1985) shows that responses from such a target only reach the 'late-time' part of their decay after several hundred seconds. Here, we have waited only 5 seconds and, accordingly, the decay rate observed is *significantly* faster than the rate you might calculate from a simple analysis of size and conductance. The obvious conclusions are that (i) the late-time decay constant of highly-conductive targets can be significantly underestimated from field data, and (ii) the use of a simple thin-sheet to model highly-conductive targets could lead to significant underestimates of true conductivity-thickness product.

For a final comparison, Figure 17 presents the response of a lower conductivity target of 400 m diameter. This target has conductivity 2,000 S/m, 10 m thickness and 400 m diameter. This model is designed to simulate the response of a typical VMS orebody—a good conductor, but not in the same category as the other targets we have modelled. VMS orebodies are typically less conductive than a massive sulphide magmatic nickel-copper orebody. Responses are plotted at same scale as Figures 12–14. Clearly, the behavior here is quite different, but there is still a strong argument for working at low frequency in order to enhance the response.

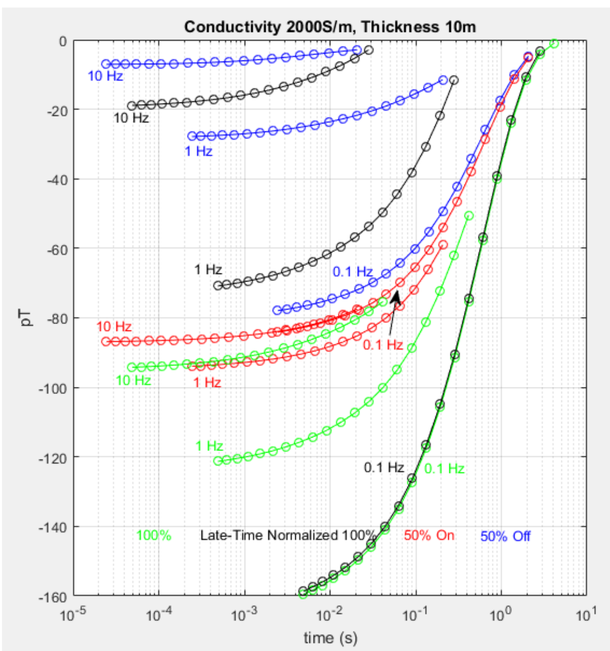

Figure 17: Decays calculated for a conductive disc of diameter 400 m, thickness 10 m and conductivity 2,000 S/m.

The above model study calculates secondary signal. One important issue to keep in mind is that these model results reflect only the predicted signal size, not the signal-to-noise ratio which is the best guide to detectability. All sources of noise must be considered, and it is particularly important to understand the size of primary fields if dealing with on-time responses. The total primary field from the transmitter loop carrying 20 A at the survey point in Figure 10 is approximately 1875 pT. Secondary fields of 100 pT are roughly 5% of the primary field and those of 20 pT are roughly 1% of the primary field. Clearly, measurements made closer to the transmitter loop will be subject to considerably larger primary fields.

It is fair to say that there are advantages and disadvantages to measuring in the on- and off-time. The above may provide some useful reference frames for deciding on measurement styles. If it is hard to decide whether to measure in the on or off-time, consider using 50% duty cycle and measuring both. Or perhaps transmit at 100% duty cycle and deconvolve data to 50% duty cycle. There are a number of options and it is important to be guided by signal-to-noise for the target and system type, and to consider all sources of noise.

EXAMPLES

Lalor VMS Deposit, Snow Lake, Manitoba

The Lalor VMS Deposit, near Snow Lake in Manitoba, Canada, was discovered by Hudbay Minerals in 2007 by following up a fixed-loop surface TEM response in data collected in 2003 (Koop et al, 2014). The Lalor Deposit is now being mined for copper, gold and zinc by Hudbay Mining. The upper parts of the Lalor Deposit are at depths of approximately 600 m below ground and the deeper parts are at approximately 1200 m below ground.

Figure 18 shows an oblique section of the Lalor Deposit and the location of a borehole (DUB178) and transmitter loop for borehole EM data presented here. Figure 19 illustrates a profile of 3-component borehole fluxgate data from a DigiAtlantis system collected in 2010 at Lalor in hole DUB178, which is approximately 200 m up-dip from the deposit, drilled roughly perpendicular to the plane of the deposit lenses. The A component is axial, U is transverse to the hole and in the vertical plane containing the hole and V is transverse to the hole and horizontal. The transmitter used here is roughly 2.5 km x 2 km and was used with a current of 18 A at 50% duty cycle at frequencies of 1 Hz and 0.5 Hz.

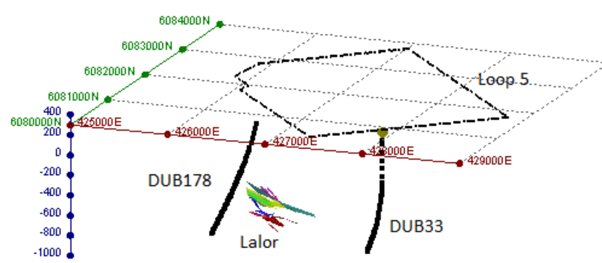

Figure 18: Geometry of the borehole TEM survey at Lalor.

The data illustrated here was collected mostly at 1 Hz, with a section through the anomaly collected at 0.5 Hz. The data presented here is from the off-time. The anomaly is off-hole (negative polarity, peaking at a depth of 600 m) on the axial component and has polarity cross-overs on the U and V transverse components.

Even though this data was collected at what was quite a low frequency for VMS TEM at the time, a total of 98 3-component readings was taken down to 1200 m for this data set in a total elapsed time of 6.5 hours.

The late-time decay constant observed on the 0.5 Hz readings was in excess of 100 msec—considered to be quite high for a VMS deposit. The late-time data fits very well to the response of a 900 m x 900 m thin sheet of conductance 800 S and corresponds well with the most-conductive Lens 10 at the top of the stack of sulphide lenses at Lalor.

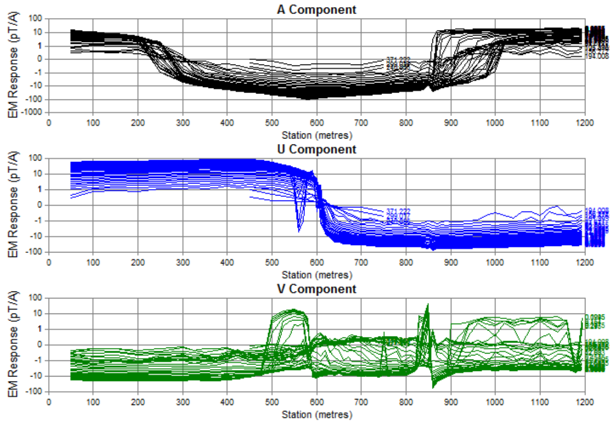

Figure 19: DigiAtlantis data in borehole DUB178 at Hudbay's Lalor. Data was collected at 1 Hz, with some stations at 0.5 Hz.

Balsam - VMS Copper/Zinc Deposit, Hanson Lake, Saskatchewan

A recent example of borehole TEM in Canadian VMS exploration at the Hanson Lake / McIlvenna Bay prospect of Northern Saskatchewan is presented here. The data presented here was collected for Foran Mining Corporation during surveys in 2013. TEM data was collected at surface and in boreholes as part of exploration around the McIlvenna Bay VMS Deposit. Following up on a surface TEM anomaly at a prospect named Balsam, along strike from the McIlvenna Bay VMS Deposit, hole BA-13-77 intersected 4.1% copper over 3.7 m (Foran Mining Corporation, 2013) at what became the Thunder Zone.

This example is presented here as an interesting comparison of the TEM responses observed from the intersection of a good conductor at different transmitter frequencies and in the on/off-time of a 50% duty cycle TEM survey. The transmitter used in this survey generated 15 A into an 800 m x 400 m loop at surface.

TEM surveys were carried out in borehole BA-13-77 using a DigiAtlantis borehole EM system at 50% duty cycle at transmitter frequencies of 2.5 Hz and 0.5 Hz for comparison. Figure 20 shows a plan of the survey location, including the location of hole BA-13-77 (the northernmost hole shown), superimposed on gridded horizontal component fixed-loop TEM data collected at surface.

Figure 21 shows a profile comparison of the 3 components of 0.5 Hz (red) and 2.5 Hz (blue) responses from delays of 18 msec and later in borehole BA-13-77. This data is from the off-time. At all equivalent delay times, the 0.5 Hz responses at the in-hole anomaly are significantly higher (a factor of 3–4 times higher) than the 2.5 Hz responses. Even the latest 0.5 Hz responses (roughly 500 msec after switch-off) are about the same size as the latest 2.5 Hz responses (roughly 100 msec after switch-off).

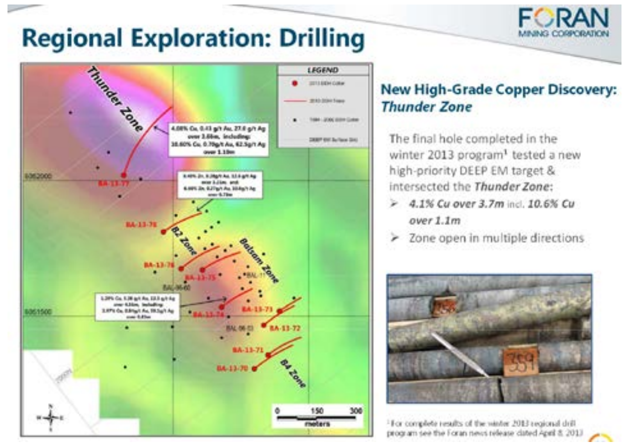

Figure 20: Plan of drilling at the Balsam Zone, superimposed on surface EM data. Presented courtesy Foran Mining Corporation.

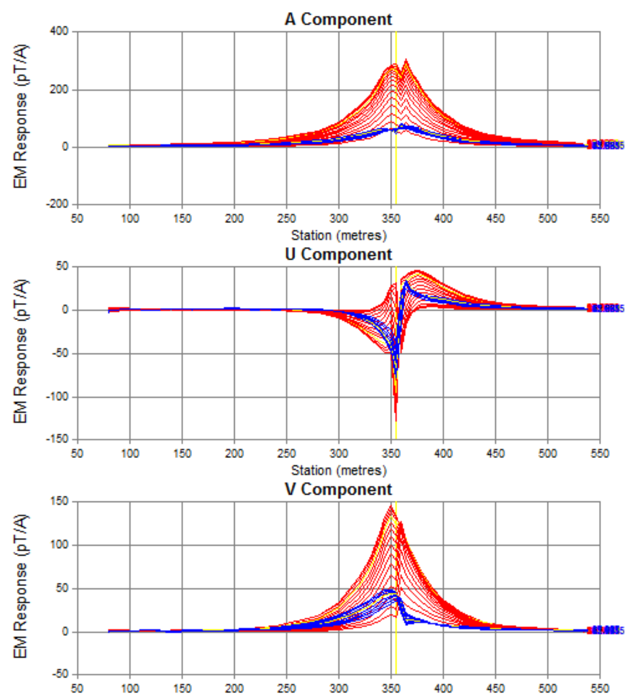

Figure 21: A comparison of profiles of 0.5 Hz (red) and 2.5 Hz (blue) borehole TEM responses in hole BA-13-77. Time windows 18 msec and later.

Figure 22 shows a profile comparison of on-time (black) and off-time (aqua) responses from delays of 18 msec and later in the 2.5 Hz data set (out to roughly 100 msec). At all equivalent delay times, the on-time responses at the in-hole anomaly are significantly higher (a factor of 5–6 times higher) than the off-time responses. On-time responses here are calculated by subtracting an estimate of the primary field, based on system geometry measurements, from the response at all time windows.

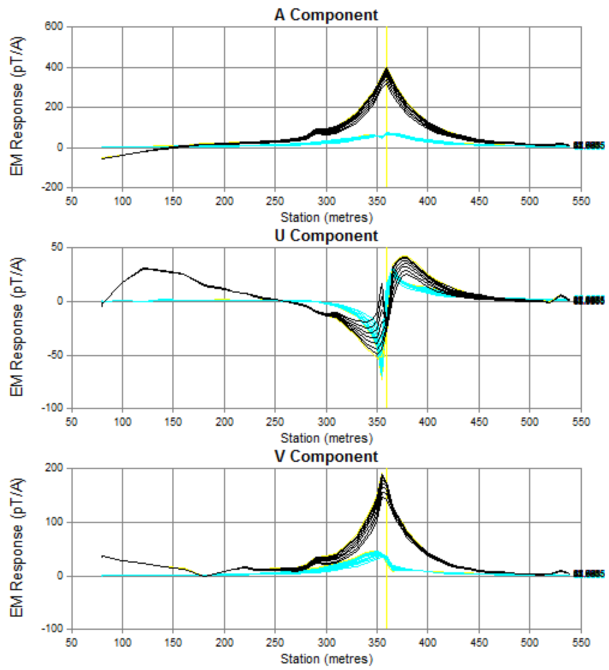

Figure 22: A comparison of profiles of 2.5 Hz on-time (black) and 2.5 Hz off-time (aqua) borehole TEM responses in hole BA-13-77. Time windows 18 msec and later.

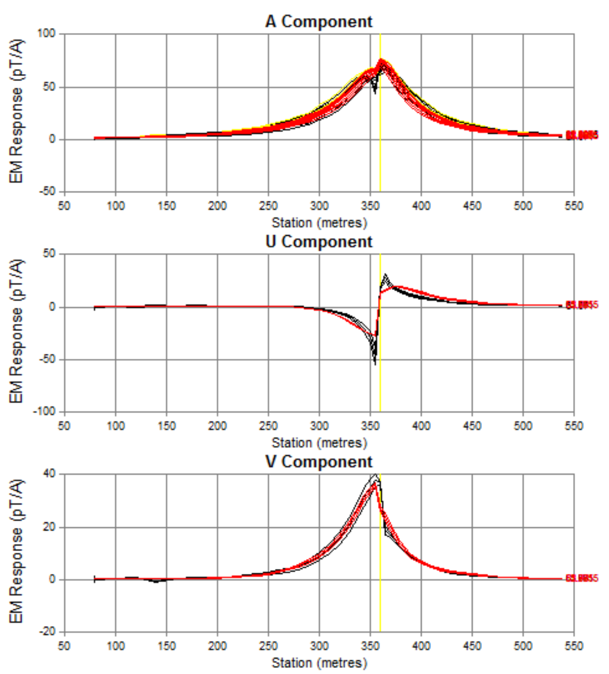

Figure 23: A comparison of off-time 0.5 Hz data (black) from BA-13-77 (time windows 50-70 msec) with a thin sheet model (roughly 10,000 S) response (red).

Lastly, Figure 23 shows a comparison of thin-sheet model response and field data for off-time 0.5 Hz responses for delays of 50–70 msec. The late-time 0.5 Hz response of Balsam Deposit in borehole BA-13-77 has been modelled fairly convincingly using a thin sheet of size 300 m x 100 m with conductance approximately 10,000 S.

Moran Nickel Sulphide Deposit, Kambalda, Western Australia

The Moran Nickel Sulphide Orebody (approximately 40,000 nickel tons) was discovered adjacent to the Long Nickel Mine at Kambalda, Western Australia, by Independence Group (IGO) in 2008. The discovery was driven by downhole TEM and was documented in Johnson (2010).

The TEM survey from a hole that passed within 20 m of the edge of Moran (not the discovery hole) is presented here. The survey employed an underground transmitter loop of size roughly 600 m x 300 m and roughly horizontal. TEM data was collected using an Atlantis 3-component fluxgate system in an underground borehole at 0.5 Hz transmitter frequency. The Moran Orebody lies about 100 m underneath one of the long edges of the loop, dipping down and away from the loop. The hole presented here is collared at the same level as the loop, about 50 m outside the loop. IGO had been using this system since 2004 as part of its nickel sulphide deposit delineation at Kambalda. Exploration work was carried out solely with low frequency off-time data from the system.

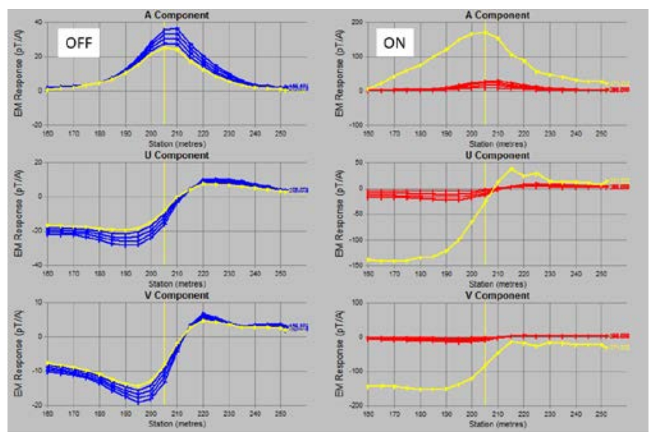

Figure 24: Borehole TEM data (0.5 Hz, 50% duty cycle) from adjacent to Moran Deposit, Kambalda. Off-time data on left and late-time-normalized on-time data on right. Time windows from 150 msec onwards.

Profiles of late off-time (left) and on-time (right) data (from delays of 150 msec and later) from this 0.5 Hz survey are presented in Figure 24, plotted against depth down hole. The last time window in each profile (centred on a delay of 370 msec) is highlighted in yellow. Both profiles are presented in the same units (but different vertical scales) and the on-time data presented is late-time normalized. That is, the latest window has the calculated theoretical primary field subtracted from it and the earlier windows have the measured late-on-time response subtracted from them.

The peak of the response from the Moran Orebody is at a depth of 205 m in this borehole, where the hole passes within approximately 20 m of the edge of the orebody. The positive axial (A) component response is in fact an off-hole response from Moran which is, in this case, reverse-coupled to the transmitter loop. The late on-time response at this anomaly is roughly seven times larger than the late on-time response, yet the difficulties in removing primary field in such close proximity to the transmitter loop result in the off-time responses having better signal-to-noise. At the latest times, the decay constant observed in the off-time data is roughly 500 msec.

A picture of a mining face through the Moran orebody (taken from Johnson, 2010) is shown in Figure 25. Moran is described as being 700 m long, 130 m wide, 10–15 m thick and with a conductivity-thickness product of greater than 300,000 S.

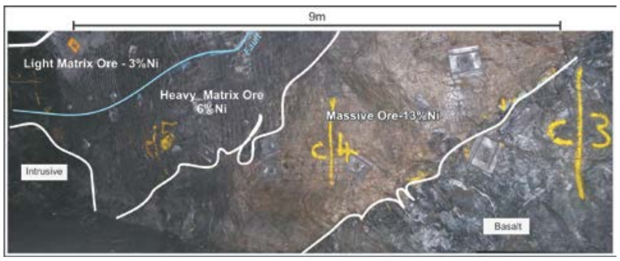

Figure 25: Photograph of a mining face at Moran, taken from Johnson (2010). Presented courtesy IGO.

Nova Nickel/Copper Deposit, Fraser Range, Western Australia

In April 2012, Australian explorer Sirius Resources announced to the Australian Stock Exchange that a moving-loop TEM survey had discovered an interesting anomaly that was coincident with nickel and copper geochemical anomalies in the Fraser Range in Western Australia. The prospect was named ‘The Eye’ after an eye-shaped magnetic feature in mafic/ultramafic rocks (Sirius Resources ASX announcement, April 2012).

The conductor was modelled from three lines of moving-in-loop (200 m square loops) TEM collected using a 3-component fluxgate magnetometer and a SMARTem24 receiver system. The model had a strike length of 200 m, a plunge of 1000 m to the northeast and a conductance of roughly 5000 S. The data on which this initial interpretation was based is not publicly available, unfortunately.

In July 2012, Sirius announced to the Australian Stock Exchange that it had discovered nickel/copper mineralization with their first drill hole to test this EM model, naming this the Nova Deposit (Sirius Resources ASX announcement, July 2012).

An up to date cross-section of the Nova Deposit is shown in Figure 26 (Sirius Resources ASX announcement). Follow-up of other geophysical anomalies and further EM surveys at the prospect resulted in the discovery of the nearby Bollinger Deposit. The deposits are currently being mined. Sirius Resources was acquired by nickel miner IGO in 2015 in a deal which valued the Nova/Bollinger deposits in excess of $AUD 1 billion.

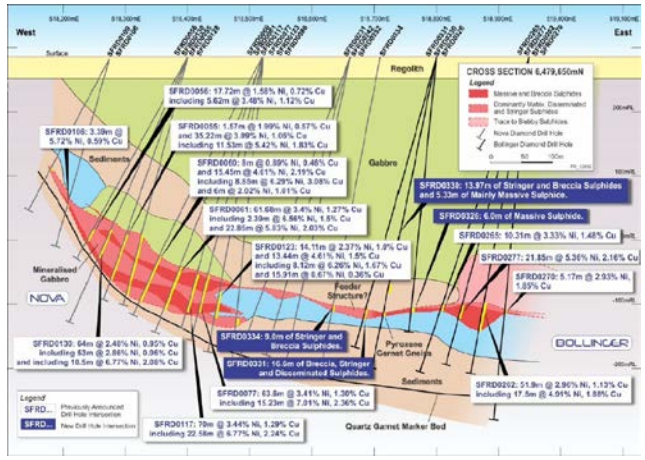

Figure 26: Cross-section of Nova nickel/copper deposit, from Sirius Resources ASX announcement.

THE FUTURE

It is my expectation that we will continue to see reductions in the frequency of TEM surveys, especially in conductive terrain and where the target is moderately to highly conductive. Necessarily accompanying this will need to be improvements in the signal-to-noise of surveys at low transmitter frequencies. Accompanying this are likely to be further developments of transmitter systems capable of delivering high current.

I would like to see tools available for simulating the response of any system to a given target, including realistic estimates of the contribution of all noise sources. These tools may need to be supplied by the contracting or equipment industry in order to give explorers an honest assessment of how a particular type of measurement will fare in a given exploration problem, but they need to be used by explorers. Of course, part of the problem is the ability to describe the geology, something that we need to work on as well. One of the results of having better simulation tools will be that we can propose optimal surveys for the equipment we have available—we can answer questions like ‘what is the optimal loop size?’, ‘what is the optimal transmitter frequency?’ and ‘how long should I collect data for?’.

More realistic modelling and inversion of TEM data will lead to the requirement for higher data density and redundancy, and higher data quality. This may be dealt with by deploying larger numbers of receiver systems, collecting more data on a survey and using multiple simultaneous measurements to reduce survey noise.

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