Geophysical surveying using raw time series recording

Polzer, Ben.[1]

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[1] Nova Mining Exploration Solutions, under contract to Vale Canada Ltd.

ABSTRACT

In early 2006 Inco Exploration completed development of the first of a series of EM, IP and MT systems based on the concept of simple field recorders of raw time series with GPS timing. Stacking and other processing procedures were done after the fact on a PC. Because the data collecting hardware that was designed could be used for many purposes, the units were termed "Universal Receivers" or URs for short. Vale took over Inco in late 2006 and continued development encouraged by the early success. Since then three surface UR systems and two borehole systems (EM and IP) have been produced based on this concept. These have been used internally to support Vale's exploration projects. The motivation for developing such systems has been driven by two factors; the pursuit of data quality at modest cost and the need to provide high quality geophysical data to exploration programs poorly served by the contracting community either by virtue of geography or logistical circumstances.

MOTIVATION AND HISTORY

In the 1990's Inco, Falconbridge and other nickel mining companies discovered the need for on-time EM to detect and accurately map the highly conductive pyrrhotite-penlandite dominated mineralization typical of magmatic nickel-copper-PGE deposits. In particular it was found that most economic nickel sulphide deposits respond when the primary field is active and have much less response in the off-time mode (West et al, 1984, Ravehurst, 1998). On-time EM gradually became essential for nickel exploration but few systems or contractors supported on-time measurements as most time domain EM systems measured in the off-time as a convenient means of primary-secondary field separation. The need for in-house equipment became clear in the early 2000s as Inco's international nickel projects expanded. With rise in general exploration activities it was difficult to find contractors with the equipment and experience necessary to conduct on-time EM surveys.

At the same time, the technology necessary for time series recording was developing rapidly. Memory card technologies had advanced to the point that a day's worth of modest bandwidth data could be captured onto a Compact Flash card and GPS technology was quite mature with many available solutions for integrated GPS timing and position. Implementing a raw time series recording system was the quickest and cheapest way to develop an on-time EM system to service Inco's nickel exploration programs. Such a system could be extremely simple leaving the complicated and CPU-intensive aspects of the processing to later on a personal computer

As the system was being developed and tested many additional advantages to this approach were realized as follows:

- Ability to review and analyze raw time series and their spectra to identify sources of noise.
- Ability to tailor stacking and pre-processing to most effectively remove the sources of noise.
- Ability to use transmitters of convenience by monitoring of the transmitter waveform followed by deconvolution.
- Ability to acquire and process data from more than one transmitter at the same time.
- Potential to accommodate low noise sensors irrespective of their frequency response.
- Deconvolution to any desired waveform for comparison to other systems and/or integration with existing data sets.
- Simplification of data acquisition allowing for unskilled operators or autonomous systems.
- Ability to conduct natural field surveys with the same equipment and in some cases at the same time.

In late 2005 a prototype of the UR-1 system was tested in Sudbury in time domain EM mode using sensors designed for MT surveys. The noise levels achieved were surprisingly low compared to controlled-source EM available from the industry at the time. In 2006 while a second version (UR-2) of the system was developed and deployed, the UR-1 system was used on 12 different projects spanning four continents (North America, South America, Europe and Australia). The success of these surveys was due to the close communications between the small in-house development team and the field crews permitting direct support for the surveys and allowing feedback for firmware and processing improvements. Most importantly the new technology development was made possible by the support of management who were eager to put it to work in exploration projects.

In 2006 Inco was purchased by Vale and exploration then included a wider variety of commodities. A third iteration of the system was completed in September 2008 (UR-3). Development then shifted to a borehole EM receiver able to operate autonomously downhole while recording the full raw time series, followed by a downhole IP/Resistivity probe based on the same concept.

In the fall of 2015 the group had the opportunity to take all that was learned in the development of the downhole systems and create a surface system to support a wide range of exploration activities for the foreseeable future. The new UR-4 system is a compact, lightweight (1.5kg), 5-channel system with automatic gain control capable of 64k sample/second continuous recording and logging. It can be married to a self-orienting tripod system for efficient 3-axis EM, or used as an MT system. The system was completed in early 2017 and will be routinely used for EM data collection within Vale for years to come.

SYSTEM HARDWARE

Low Noise Sensors

From the start, use of extremely low-noise sensors was a priority. Geomagnetic noise limits the precision of controlled-source measurements of electric and magnetic fields. Above 8Hz, geomagnetic noise is due to "sferics", the electromagnetic pulses from individual lightning strikes occurring globally on average 50 times per second. Magnetotelluric (AMT) surveys utilize the sferic pulses as their source and their sensors of necessity have a noise floor well below the geomagnetic signal. The induction feedback coils adopted for the UR system were based on MT sensors designed and built by Geotell Research, which were available commercially through Zonge Engineering. Two versions were produced for Vale, the ANT3 and the ANT23. The ANT3 has better low-frequency performance with a noise floor of 100fT/sqrt(Hz) at 1Hz but is longer and heavier (38 inches and 3.5kg). The more compact ANT23 (24 inches and 2 kg) has a noise floor of 500fT/sqrt(Hz) at 1 Hz but has a lower noise floor at higher frequencies. Figure 1 compares the noise spectral densities of these sensors against that of the Bartington fluxgate magnetometer.

While offering a noise floor well below that of air cored sensors of similar weight, the spectral response of induction feedback sensors are not convenient for use as TDEM sensors. In particular their response to a magnetic field signal is significantly distorted. Transmission of a typical 50% duty-cycle castle waveform into a loop will result in a sensor response with a significant decay in the off-time. This distortion must be corrected by deconvolution for time domain applications.

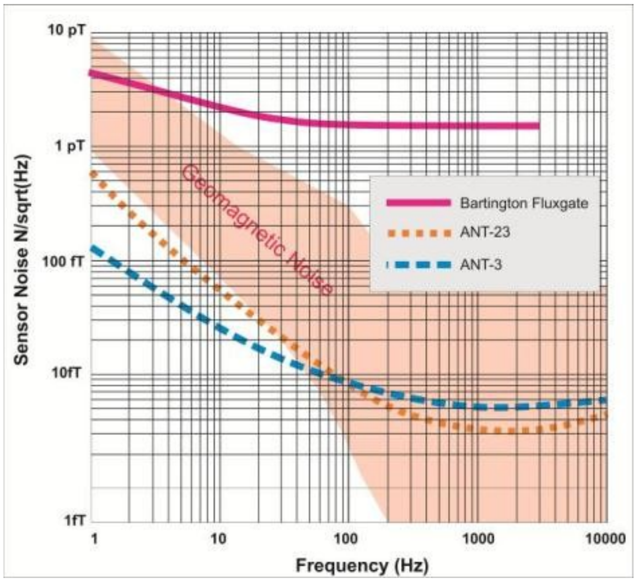

***Figure 1**: Spectral noise densities of the magnetic field sensors used by the various UR systems.*

Transmitters of Convenience

Because the UREM system relies on current monitoring and signal processing, the system can utilize a wide range of transmitters. Because of their low cost and availability, Vale has made use of high-quality off-the-shelf audio amplifiers driven by laboratory function generators. The waveform is typically a 100% duty cycle square wave. A relatively underpowered (60V) but high-fidelity amplifier was used for the first several years of operations, and would provide only 1 or 2 amps into large loops (1km-2km). Over the years higher voltage amplifiers have been adopted (150V and 240V). By using this strategy the necessary equipment for a transmitter including the generator can be sourced in almost any location for under $10,000.

Surface Receiver Models 1-3

The first URs (models 1-3) had 8 input channels with separate input cards for each channel. The idea was to make them truly universal whereby the analogue cards could be specialized for different applications and sensors such as EM, MT, Seismic etc.. Over time, the system has been mainly used for EM, IP and MT. These variants of the system are called UREM, URIP, and URMT.

The UR-3 was completed in 2008 and operated until 2016 when it was replaced by the UR-4 which offers many logistical, operational and technical improvements.

One of the first UREM surveys conducted with the UR-1 was in northern Finland in the winter of 2006. A number of factors made data from this survey some of the quietest ever collected by a UR system. These factors included the remoteness of the site, the relative lack of sferic activity, and the use of deep fresh snow for burying and leveling the vertical component sensors. Data from this survey provided an early appreciation of the extremely low noise floor of the system. As an illustration of this, data from a single station have been analyzed to estimate repeatability. Figure 2a shows four 15 second stacks of the vertical component that have been excised from a 60 second reading taken 1000m from a 300m x 600m loop carrying a 2Amp 25Hz 100% duty-cycle square wave. The data have been stacked onto 64 linearly-spaced time channels across the waveform half-cycle with the transition lined up by a triggering algorithm after the fact. The primary field amplitude is about 15pT and the four stacked waveforms are indistinguishable at this scale. The four stacks are slightly different in amplitude at the sub-percent level reflecting slight systematic changes in coupling during the measurement. To explore the level of non-systematic noise processes that will affect the waveform shape, waveforms C-D have been scaled by different amounts so as to match the amplitude of waveform A. Figure 2b shows the standard deviation of the four independent-scaled waveforms. It is below 15fT from channel 12-53 then rises to abut 20fT at the end of the half-period. The large values at early times (channels 3-11) likely reflect timing errors in the triggering process used for this analysis.

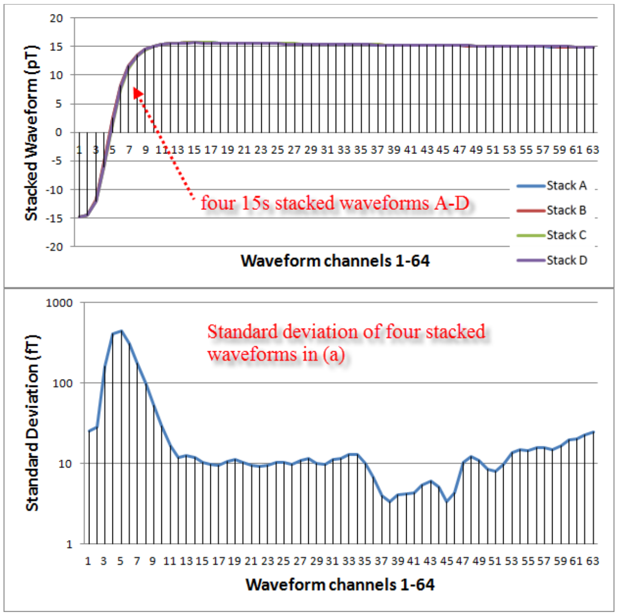

***Figure 2**. Four 15 second stacked waveform half-cycles are shown superimposed (a) for a vertical component collected 1000m from a 300m x 600m loop carrying a 2A 25Hz 100% duty-cycle square wave. (b) The standard deviation of the four waveforms in (a) for each of 64 evenly-spaced time channels across the half-cycle.*

In most situations, the repeatability is far worse due to ambient cultural and sferic noise. It is typically between 20fT and 100fT range for 60s readings at 30Hz repetition rates in most environments showing that the dominating noise sources are not instrumental but are likely geomagnetic.

Since 2006 the UR systems have been used for fixed-loop EM and MT surveys in Canada, Australia, Brazil, Mongolia and Finland. Right from the first surveys they have produced outstanding data. In 2007 a survey was conducted in Thompson, Manitoba, as an extension of previous coverage by a commercial system (CSYS). To gain confidence in the new system a full loop of CSYS data were recollected for comparison. The UREM data were processed to match the CSYS waveform and time channels. At the time only a 60V audio amplifier was available so the UREM data were collected with less than half the loop current and were stacked 40% less time. Despite these disadvantages the comparison for the four lines of coverage shows the UREM data to have about 5 times lower noise. Figure 3 compares the vertical component data for a single 5700 foot long line. The UREM data have been collected at twice the station density and show subtle details in slope inflections reflecting changes in current density at lithological contacts. Because the UREM data can be reprocessed with any system response, their lower noise allows the data to be stacked to a much higher temporal channel density allowing for better sounding and inversion.

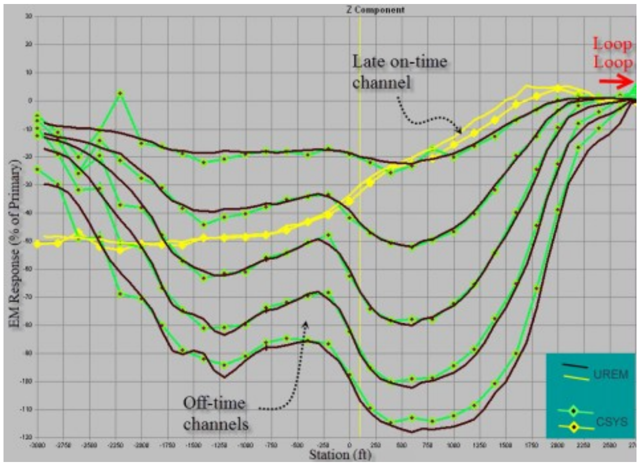

Figure 3: *Comparison of UREM data with data from a commercial system collected in Thompson MB. The UREM data were collected at twice the station density with 40% less stacking time per station and less than 1/2 the loop current.*

Because of its low noise and flexibility, the UREM system was able to be used in many different environments. Figure 4 shows reconnaissance work conducted on a property in Brazil where the logistics and access was not conducive to large-scale surveys as access to the different survey sites required negotiations with different landowners. A series of small ultramafic intrusions were explored using a locally hired crew headed by a geophysicist/processor. Moderate sized loops (300m x 300m) were positioned at the centre of each intrusion and lines were surveyed outward in a star pattern thereby exploring the intrusion margins for conductive sulphide mineralization. The use of in-house equipment and a local crew kept survey costs low despite the slow progress due to difficult access and logistics.

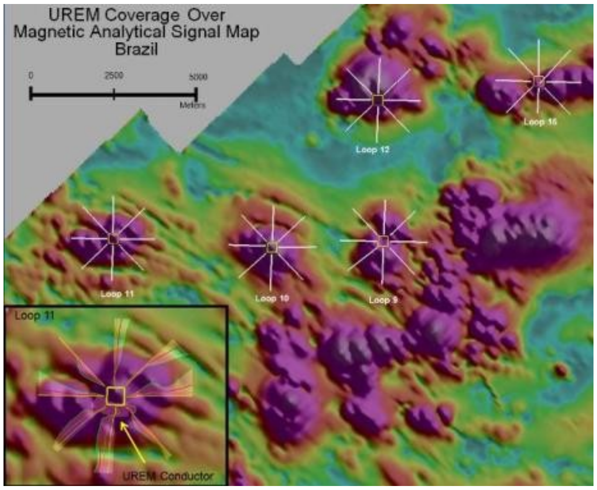

Figure 4(a): *Reconnaissance UR3 survey grids plotted on total magnetic intensity in Brazil. Small (300m x 300m) loops were placed at the centre of small intrusions. Radial 1200m lines were used to test the intrustion margins for sulphide deposits.*

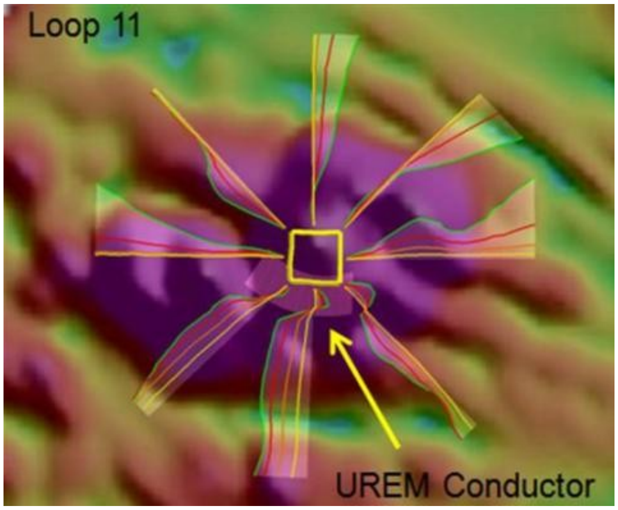

Figure 4(b): *Detail of Loop 11 UREM response from Figure 4a showing UREM anomalies at southern margin of intrusion.*

The URMT System

By 2010 Vale had a large inventory of UR-3 receivers and magnetic sensors, and it was only natural that the system, being designed as a general purpose time series recorder, should be used for magnetotelluric (MT) surveys. A two-channel electric-field preamplifier was designed and built, and a robust remote-referenced MT time series processing workflow was added to the UR processing software suite. Procedures necessary for system validation, data QC and data acquisition were developed and disseminated in a series of training sessions. Figure 5 shows a single MT sounding taken in Brazil using the UR-3 system.

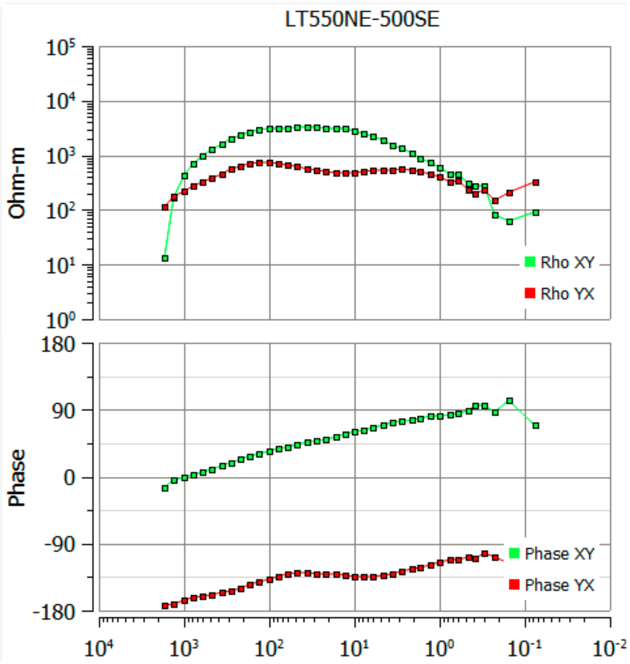

***Figure 5**:* *UR-MT sounding from Brazil collected with the UR3 system. Good apparent resistivity and phase can be obtained from about 0.2Hz - 1kHz.*

The UR-3 does have some limitations as an MT receiver. Its limited bandwidth of 8kHz sampling makes it difficult to acquire useful information above the MT dead band (above 3kHz). It has adjustable gain that is fixed for the duration of the reading. Data can be rendered useless if ambient signals suddenly increase during a reading causing the inputs to over-range. Without downloading a short time series to a laptop, there is no way to validate the quality of the signals and the integrity of the sensor connections. The nightly data downloads are slow. All of these issues were corrected in the design of the subsequent UR-4.

The Borehole EM System (BH-UREM)

By the 1990s borehole EM technique had proven usefulness in exploration and resource definition. The method is best applied after the completion of each hole so that exploration decisions can be made in a timely manner thus making best use of limited drilling budgets. The costs however associated with getting BHEM systems and crews to a remote project after hole completion were usually too high to justify. Costs to the project can escalate further as shipping, importing, customs delays and associated standby charges can spiral out of control. With this in mind, Vale set out to create a low-cost, effective borehole EM system in support of its global exploration projects. Based on the "universal receiver" concept, the BH-UREM system was different from any previous downhole EM probes. The entire UR receiver was packaged inside the probe allowing full time series data to be collected downhole with no link to the surface. In other borehole systems, the heavy winch and cable required for up-hole data transmission are an expensive and heavy part of the system. In contrast the BH-UREM probe can be lowered on a Kevlar cable deployed from a lightweight winch used for dummy probing of existing holes or on a drill wireline. Because only a PC is required at the end of the day for downloading the data, the system eliminates an expensive receiver.

To realize this degree of autonomy and provide for a wide dynamic range, the system incorporated an auto-gain system, GPS time synchronization at the collar and a high-precision crystal clock allowing the probe to maintain an absolute time reference while logging downhole. A companion depth encoder recorded depth as a function of time for later reconciliation in post-processing. The probe provides for three channels continuously acquire at 32000 samples/s for 12 hours.

The BH-UREM probe used the convenient and readily available Bartington fluxgate sensor used by a number of other borehole EM probes in the industry. For the common frequencies of 4Hz and above this sensor is up to fifty times noisier than other induction sensors (Figure 1). However, it is conveniently packaged, inexpensive, and can do a reasonable job in many settings, particularly in resource definition roles where signal/noise is not always important. To provide for a lower noise solution in situations where seeing as far as possible from the hole is important, a borehole version of the ANT-3 sensor was designed by Geotell. The high-sensitivity axial (HSA) probe was then deployed in a modular fashion as shown in Figure 6. The upper section comprises the receiver with its digital and analogue boards as well as orientation sensor and GPS. The lower section houses the sensor; either the Bartington fluxgate or the low-noise feedback induction sensor.

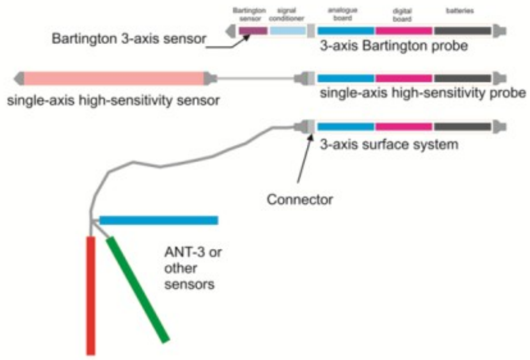

Figure 6: *BH-UREM probe configurations.*

The BH-UREM system was first tested in Sudbury by comparing it to data from the borehole UTEM-4 system. With an excellent 3-axis downhole feedback induction sensor, Lamontagne's UTEM-4 probe has a much lower noise floor than the Bartington sensor so the BH-UREM probe was not seen as a replacement for UTEM-4 but rather as a means of providing convenient in-house borehole EM capabilities when logistics or timing made it difficult to get UTEM-4 surveys done. Figure 7 shows a comparison of late channel data from a hole located in Sudbury. The profiles compare well for this case where signal levels are high.

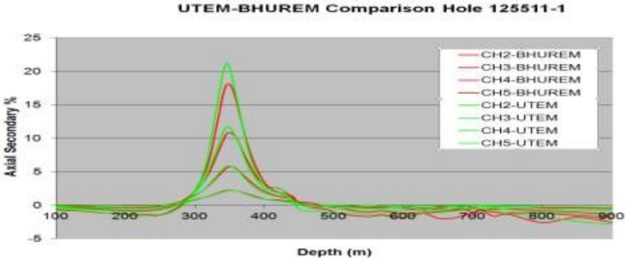

Figure 7: *Comparison of late time channel data between UTEM-4 and the BH-UREM system using the Bartington fluxgate sensor.*

To provide information on a more difficult target, the BH-UREM system was tested at the Caber VMS deposit in Western Quebec. Hole 99-56 undercuts the deposit by 200m and provides a good test of off-hole detection capabilities. Figure 8 compares the response of the axial component using the 3-axis Bartington fluxgate sensor (left) to the same survey repeated with the high sensitivity axial sensor (HSA) on the right. While the anomaly is clearly detected by both sensors, it is unlikely that the interpretation of the Bartington sensor data would permit detection at a range much more than 300m. In contrast, the HSA sensor response is very clean. With a noise floor more than 50x lower than the Bartington, this sensor would likely detect the same anomaly up to 4 times further in ideal conditions of low sferic activity.

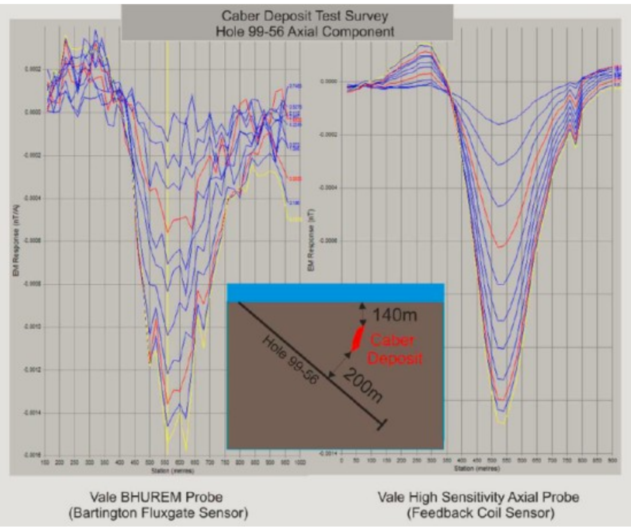

Figure 8: *BH-UREM responses of the Caber deposit from Hole 99-56 located 200m away. Axial components of the Bartington fluxgate sensor (left) compared with the high sensitivity axial sensor (right).*

When using the Bartington fluxgate magnetometer sensor, the BH-UREM probe is a self-contained EM system. It can therefore be used as a surface EM system by carrying it from station to station, placing it on the ground for each reading. The stations are identified in post processing as the intervals of low acceleration allowing each station's time series to be excised from the continuous data set. This capability allows surface traverses to augment borehole data sets without the need for deployment of a separate surface system. Simultaneous modelling of surface and borehole data can provide better definition of shallow targets.

The BH-UREM probe has also been used as an acquisition system for surface sensors (Figure 6, bottom probe configuration). In 2012 a new technique was tested on the Melville Peninsula in Nunavut Canada. The "Groundfloor EM" method used a series of fixed receiver stations on the ground located in key locations relative to favorable geological features. Data were collected continuously from a VTEM airborne survey that was conducted overhead. Using principles of reciprocity, the data were processed to yield equivalent ground-loop-based data providing a valuable on-time component to the VTEM survey (Bengert 2015).

The BH-URIP System

Exploration for copper mineralization, and disseminated magmatic sulphides commonly includes conducting resistivity and induced polarization (IP) surveys to detected disseminated sulphides. Inversion techniques have helped considerably in understanding the source of IP anomalies, however it is not always clear if a resistivity and/or chargeability anomaly has been intersected in drilling and once a hole is drilled there are few geophysical options to vector towards better mineralization. To help provide data to support galvanic vectoring techniques, a downhole IP probe (BH-URIP) was designed and completed in 2015. The 36mm autonomous probe boasts 16 channel simultaneous acquisition at 24-bits with auto-gain at 16000 samples/s and it is married to a 17-electrode string which hangs below it.

Figure 9 shows an example of profile apparent resistivity and chargeability for a mineralized borehole in Sudbury. With the ability to collect data from 16 electrode pairs at a time, such profiles can be collected very efficiently with 5m electrode spacing. Figure 10 shows the stacked decay curves for the 16 profile stations corresponding to a simultaneously-acquired spread as highlighted in Figure 9. The decays are clean near the top of the interval with VPs ranging from 20mV at a depth of 527m to 2mV at 577m. Below 577m the Vp drops to the uV range as the sensors enter the mineralization. Testing has shown the probe's noise level to be comparable to or better than several commercial surface-based IP receivers.

While simple gradient profiling can be quite useful, the probe is also being used increasingly in generating data for inversions for vectoring from a single hole by moving the transmitter locations on surface, for imaging between holes by using transmitter poles downhole and by combining borehole IP/resistivity data with similar data from surface surveys. When working in and around a group of holes, it is better for the resolution of deep structure to maintain a point of common potential on surface to which all measurements can be directly or indirectly referenced. Variants of the "common pole" technique (Bengert 2012) are realized by extending a reference conductor from the common pole to the first electrode of the string down hole. In this way, accurate measurements across each electrode pair can be made for resolution of local structure while accurate potentials can be determined between any two potential pairs on the survey thereby constraining large-scale structure.

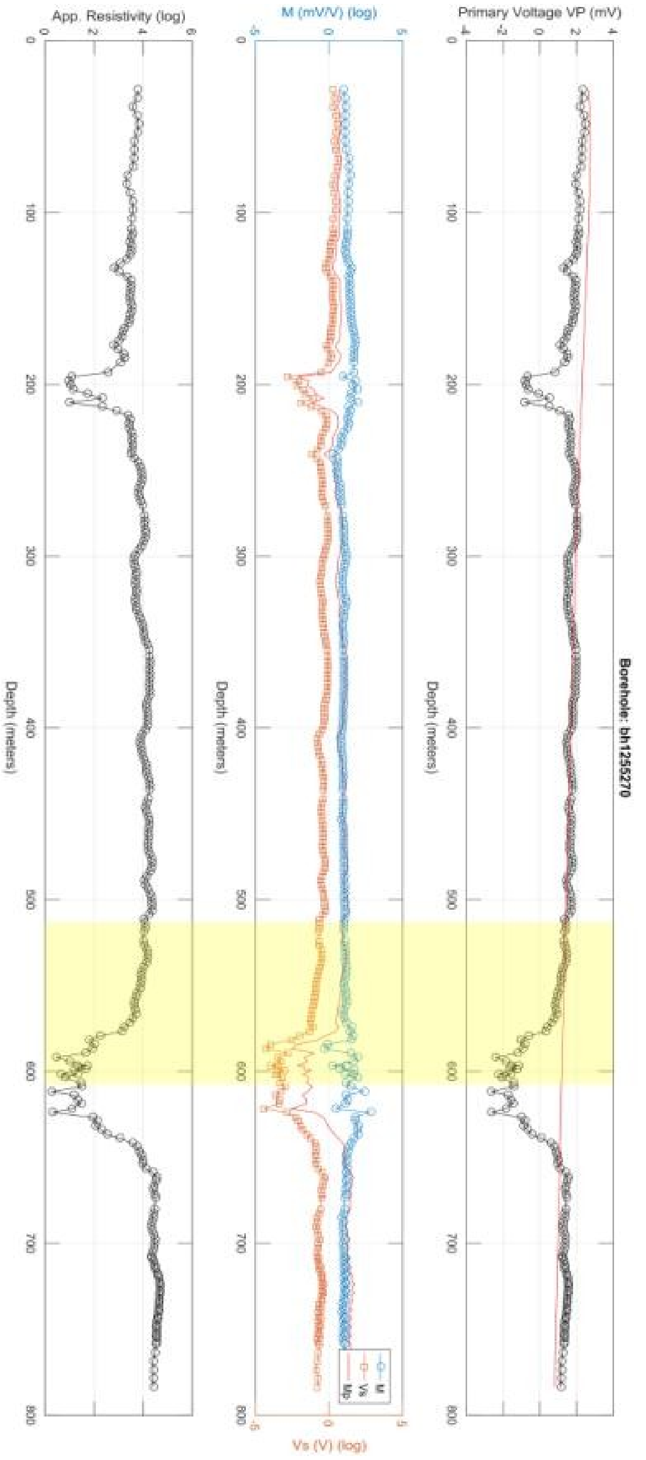

Figure 9: *BH-URIP log for hole in Sudbury Basin. The data were logged with 5m electrode spacing with the transmitter surface bipole in a fixed configuration.*

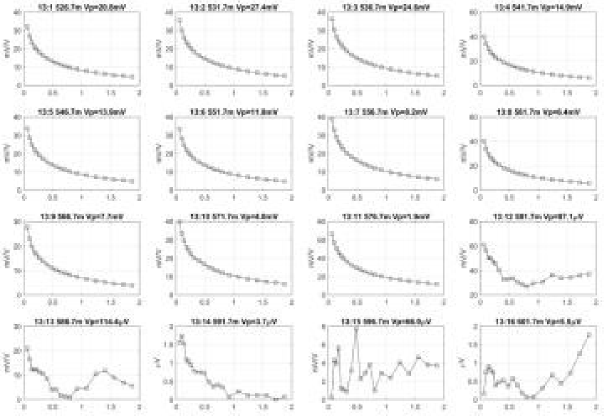

Figure 10: *IP decay curves for the simultaneously acquired spread corresponding to the shaded section of the hole as illustrated in Figure 9.*

The UR-4 System

The UR-3 system was used for many years collecting low noise data, but it suffered from a number of design and implementation limitations, as well as some reliability issues. In the seven years since its inception, two borehole probes were designed giving the Vale design team valuable lessons in systems integration and miniaturization. In the fall of 2015 after a consultation process with internal users, the UR-4 development program began. The first field prototypes were used for production surveys in Sudbury in the fall of 2016. The UR-4 receiver is a significant improvement over the UR-3 it replaced (Figure 11).

Figure 11: *Comparison of the UR-3 and UR-4 receivers.*

- 6 times lighter at 1.2kg.
- Sample rate increased to 64kHz.
- Fast data downloads through dedicated hardware USB controller.
- GPS timing with holdover for use underground.
- User interface on Android device through WIFI allowing for viewing of data as raw time series, stacked waveforms, or spectral density plots.
- Short Burst Data (SBD) network modem connection for remote control and remote monitoring anywhere in the world.
- Hardware and firmware for determination of orientation of a 3-axis sensor tripod.
- 5 fully integrated channels making it useful as an MT receiver.
- High level of integration making it easy to assemble with a minimum number of wires and connectors requiring hand fabrication.

The UR-4 Sensor Tripod

One of the first surveys anticipated for the UR-4 was 3-axis EM facilitated by use of an easy-to-orient sensor assembly. A tripod was designed, field-tested and refined. Its three legs fold out into a mutually-orthogonal configuration. The large diameter legs not only provide for a high degree of stiffness, but they incorporate the sensors themselves. The head on the tripod includes an orientation device incorporating a three-axis magnetic sensor, accelerometer and gyro (Figure 12). Data from the magnetic sensor and accelerometer are collected automatically for a few seconds before and after each reading. These data can be used in a number of ways to compute the orientation of each sensor in the "world frame" depending on the intensity of local magnetic anomalies. All the electronics in the head are shut off during the EM data acquisition. The gyro has a very low drift of about 3 degrees per hour. It is activated at the end of the EM data acquisition phase and operates continuously until EM data are next acquired, usually at the next station. The gyro provides an accurate relative orientation of the tripod assembly from setup to setup. Based on minimizing the variance in the gyro-predicted magnetics over the length of the line, an optimization algorithm is used to simultaneously recover the gyro drift and robust estimates are made of the tripod orientations during the day.

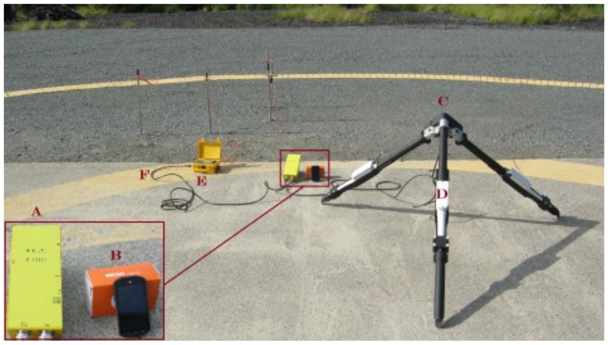

Figure 12: *UR-4 receiver (A) connected to its 3-axis EM tripod (C) and optional electric field pre-amp (E). The tripod incorporates the EM sensors (D) into its legs.*

UR-4 3-axis data

Since the fall of 2016, the UR4 system has been used in 3-axis mode for surveys in the Sudbury area. The surveys have served to battle-harden the systems to the rigors of field use and to refine the processing, QC, data integration and display. Figure 13 shows an example survey from the Sudbury contact environment. Multiple zones of plunging mineralization are expressed as short strike-length conductors from surface; a challenging environment for interpretation of single-component data and a perfect case-study for the benefits of 3-axis EM.

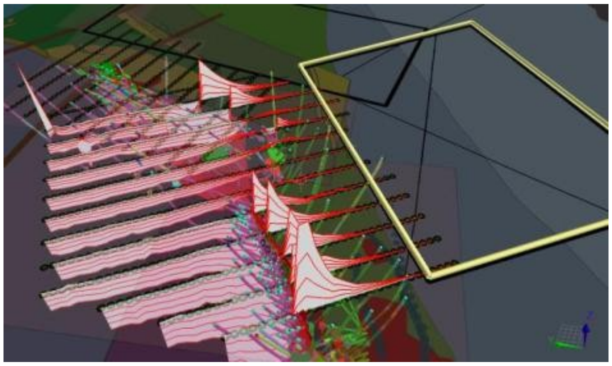

Figure 13(a): *UR4 data over Sudbury Ni-S mineralization (Bz).*

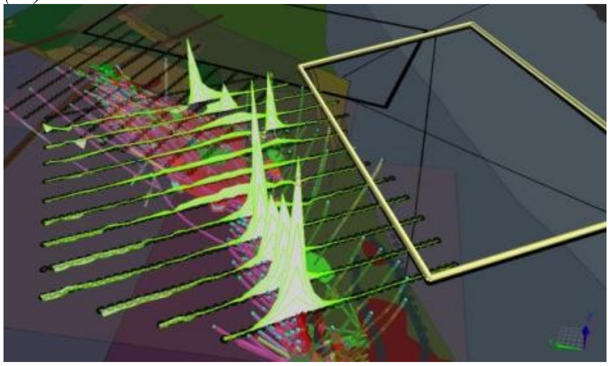

Figure 13(b): *UR4 data over Sudbury Ni-S mineralization (Bx).*

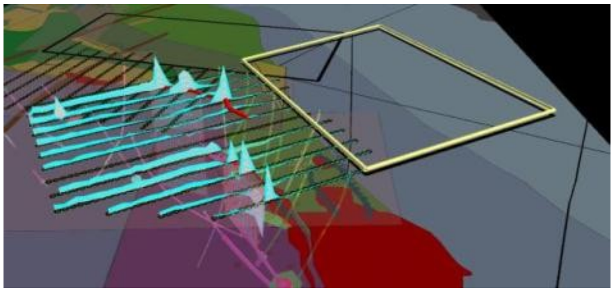

Figure 13(c): *UR4 data over Sudbury Ni-S mineralization (By).*

SYSTEM PROCESSING

A large part of the UR systems is the post-processing component which occurs on a PC usually in the evening following each day's survey. For EM and IP, the first stage of processing is stacking. By stacking data after they are collected, stacking and other processing steps can be optimized for suppression of particular types of noise (Macnae et al, 1984). For the purposes of stacking, a large number of time channels (usually 1024) are evenly distributed across the period. To avoid aliasing the number of channels is chosen to reflect a sampling rate somewhat higher than the raw sample rate. At each station, the synchronized Tx and Rx time series are stacked onto these time channels by integrating the interpolated time series across each channel interval. Averaging functions other than the classic boxcar can be applied in this step to target specific noise sources.

The sensor, transmitter loop and receiver electronics all conspire to distort the stacked signal from a desired reference waveform, usually a 100% duty-cycle square wave. The UR processing software makes use of deconvolution to solve this problem. The entire process is summarized in Figure 14. The process relies on the computation of least-squares deconvolution filters to correct for the distortions imposed by the sensor response as well as the response of other parts of the system. The filters are applied to the synchronized stacked waveforms of the receiver and the current monitor sensing the current in the transmitter loop.

Figure 14(a) shows a process that is done once per day or once per survey. A square wave calibration voltage signal is introduced into a calibration winding around or near the sensor. Because of the sensor response function, the inductance in the coil and imperfections in the voltage signal, the output logged from the sensor (S_{txc}) is not square. Similarly, data from a sensor is logged (S_{rxc}). In addition to the distortions from a perfect square wave as observed in S_{txc}, S_{rxc} has additional distortion due to the response function of the sensor. A least squares deconvolution filter, F_{rx} is determined in a two stage process described in Figure 14(b). This filter undoes the distortion caused by the sensor.

During the survey a reference waveform (usually 100% duty-cycle square wave) is injected into the loop amplified by a general-purpose linear amplifier, Figure 14(c). The current in the transmitter loop is monitored with a current monitor and receiver (S_{tx}). A least-squares deconvolution filter, F_{tx} is determined which transforms S_{tx} into S_{ref}. This filter accounts for the distortion from S_{ref} caused by imperfect transfer functions of the voltage source, the amplifier, the loop impedance, the current monitor and the receiver. Of particular importance is accounting for the loop impedance which is a function of time as it changes slowly as the wire's resistance changes with temperature. The two filters F_{rx} and F_{tx} are applied to the observed data S_{rx} to correct for all distortions except those of the current monitor. For this reason use of an extremely high fidelity current monitor is particularly important.

The process assumes that all receivers and current monitors have the same transfer functions independent of gain and temperature. Experience and testing has shown that the process fidelity is good to a few hundred ppm.

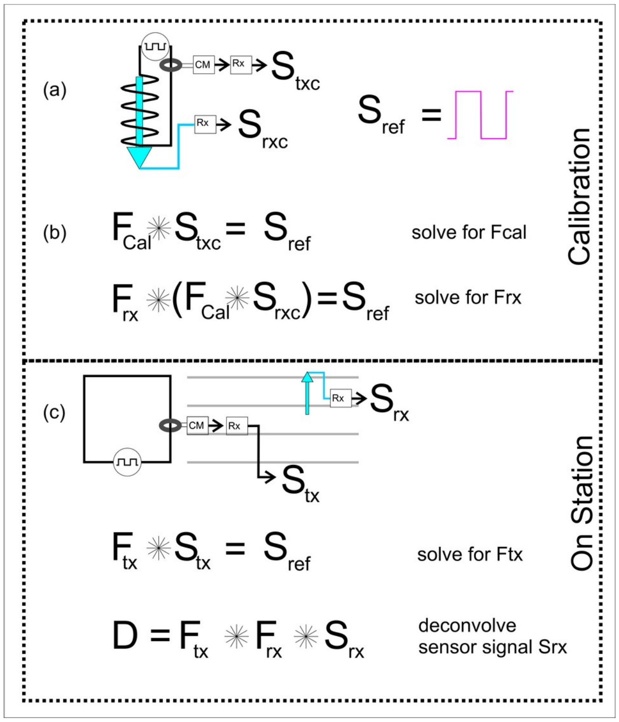

Figure 14: *UREM processing schematic. Processing targets a reference waveform (S_{ref}), usually a 100% duty-cycle square wave as shown here. (a) Experimental setup and signals for calibration of sensor. (b) Determination of deconvolution filter to correct the sensor (F_{rx}). (c) Measurement of data at each station. Data from the transmitter (S_{tx}) are stacked in sync with data from the receiver (S_{rx}). A deconvolution filter Ftx is determined from S_{tx}. It accounts for the deviation of the current waveform from the reference waveform. Cascaded with F_{rx} determined in (a) it is used to deconvolve the receiver signal, S_{rx} to D.*

CHALLENGES

Data Size

There are a number of challenges related to time series processing of controlled source data after the fact. The most obvious is the need to manage very large data files. A typical 3-axis EM survey can generate over 2.0GB/hr for 3-components at 64k sampling. It is certainly a lot easier than it was 10 years ago and the barriers based on data size will continue to diminish as hardware becomes more capable. Further streamlining however has been done to mitigate this in the meantime. Once a basic stacking strategy has been decided upon, data for each station can be pre-stacked and cached. Further processing including deconvolution is done on the stacked waveforms as access to the original data is no longer required.

Project Management

Because the same gear can be used to support a wide variety of survey types and the processing can be optimized for the conditions, there are a great many options in the processing workflow that can make processing somewhat confusing. These issues have been mitigated to some extent by the creation of processing workflows for the main survey types. Each workflow preserves references to the input files and processing parameters so that the data can be reprocessed semi-automatically if required. A batch process has been created to iterate the workflows through each day's data from each receiver.

Dynamic Range

The strategy of using the lowest noise feedback induction sensors and full duty-cycle waveforms limits dynamic range. The fidelity of the deconvolution process as it has been practiced is limited to several hundred ppm. This makes it difficult to realize the true noise floor for survey geometries that have the receiver very close to the loop. For instance, poor results can be expected for a close-couple moving loop configuration where the primary field is more than four orders of magnitude larger than the noise floor. For such surveys, a bucking scheme or a form of null-coupling may be required to improve survey quality.

FUTURE DIRECTIONS

Remote Reference Noise Removal and Transfer Function Generation

For any controlled source system using sensors capable of characterizing the geomagnetic spectrum, geomagnetic noise becomes the noise floor. Remote reference techniques can be applied to simultaneously remove this barrier and to take advantage of the geomagnetic signal to gain a valuable additional data set complementary to the controlled source survey. Figure 15 shows how this can be done. The figure shows the layout of a 3-axis EM survey with a remote reference station recording two components Bx and By. Time series of each component, D_i, contain signal from the same sferics recorded at the remote site however these sferic fields have been distorted by the conductivity distribution within the earth. In the figure, the ~ denotes Fourier transforms of the time series measurements. The distortion can be characterized by a set of transfer functions in frequency domain, T_{xi} and T_{yi}, relating the x and y component sferics as observed at the remote site to each of the observed components on the grid. The transfer functions can be computed by many means as is common in MT processing. These functions can be used to predict the fields of the sferics at the survey location using the observed sferics at the base station. These predicted sferics in turn can be subtracted from the observed time series. This process can theoretically remove the sferic noise completely while increasing the sensor noise by the square root of two and as such it is useful if the noise floor of the sensors is well below the geomagnetic signal level.

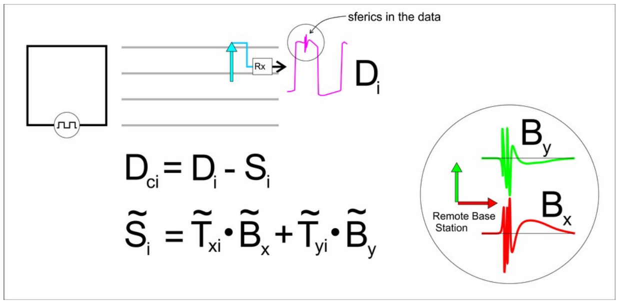

Figure 15: *Sferic noise removal by use of a remote reference station. Transfer functions between the magnetic field at a station and the magnetic field at the base station are computed in the frequency domain using standard MT methods and used to predict the sferic signals at the station. These are subtracted from the data before stacking.*

In addition to being useful in their role in reducing sferic noise, the transfer functions can be valuable complementary exploration tools. The geomagnetic field is largely horizontal and couples well with structures that are not coupled well to the field of the transmitter loop. The transfer functions can be used to generate time domain responses of virtual horizontally-polarized sources. For convenient comparison to the UREM data, the virtual sources can be made to have a square wave excitation with the same repetition rate as the UREM survey by multiplying the transfer function by the Fourier transform of the square wave. After inverse Fourier transformation, transients will be those of a horizontal magnetic field applied with a square wave excitation. Since transfer functions are derived for two orthogonal source excitations, the virtual horizontal square wave field can be rotated to any azimuth, each azimuth giving a different 3-axis transient survey across the grid. (Figure 16).

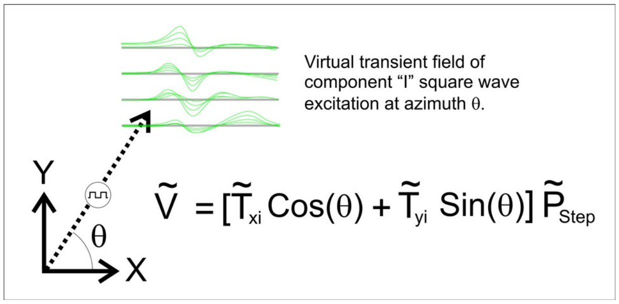

Figure 16: *From computed step responses, the virtual transient response can be computed for any temporal excitation such as a square wave, and for any azimuth of polarization, q.*

CONCLUSIONS

Over the past 10 years Vale have developed a number of EM, MT and IP systems to support their worldwide exploration projects. These systems record raw time series from low-noise sensors and achieve stacking, deconvolution and other processes on a PC at the end of each survey day. This approach has many advantages. It allows the receiver devices to be kept simple, lightweight and inexpensive. Access to the raw time series data along with precise absolute timing allows advanced techniques to be applied for noise suppression and for extraction of additional information. Moreover, as new processing techniques are conceived they can be applied to existing data sets both to facilitate their development and to extract new exploration insights.

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