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Examples from a new EM and electrical methods receiver system

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ABSTRACT

The SMARTem Electrical Methods Geophysical Receiver System has evolved during the last three years as a flexible new tool for TEM, IP and other electrical geophysical survey methods. This paper presents a brief description of that instrument and several examples of data collected recently in Australia.

First prototyped in mid-1995, the SMARTem receiver is now increasingly used in mineral exploration and ore delineation geophysics. Based on a rugged PC with a familiar operating system and programmed in a high level language, its aim is to increase the value of the data obtained in electrical geophysical campaigns. In addition to carrying out geophysical tasks in a graphics-rich environment it functions as a digital storage oscilloscope and spectrum analyser. SMARTem has been used in fixed-loop, moving-loop, borehole (axial and 3-component) and underground surveys in both direct-trigger and crystal-synchronised modes.

TEM data from Leinster and Kambalda in Western Australia illustrate the use being made of SMARTem in the exploration for nickel deposits in Western Australia. Data is typically collected in or around existing mine infrastructure where electrical interference from power grids and other sources is significant. Signal and data processing strategies have been developed and optimised to allow data of the desired quality to be collected at good rates of production. Software for automated acquisition and processing of 3-component borehole TEM data has been developed.

At Honeymoon Well, Western Australia, SMARTem work has been carried out over the Wedgetail Deposit – a popular site for tests of TEM instrumentation. Fixed-loop and moving-loop TEM data from the site is presented to illustrate this instrument's performance in the mapping of this very difficult geophysical target.

Recently, SMARTem borehole TEM data has been collected underground at Mount Isa in the exploration for new deposits in the Deep Copper mine. This environment is especially difficult for TEM as a result of interference from underground equipment. Examples of data sets and processing results are presented.

Keywords: TEM, receiver, interference, data acquisition, nickel, copper.

INTRODUCTION

A new electrical geophysical methods receiver system, SMARTem (Figure 1), completed its first surveys in 1995 (Duncan et al., 1997). This system, with a PC architecture, was developed to provide a flexible platform for measurement, analysis, processing and display of signals in TEM, IP and other electrical geophysical techniques.

SMARTem was developed with the aims of boosting data quality and survey productivity by:

Figure 1. SMARTem receiver (left) and SMARTem synchronised remote transmitter controller. Note the VGA-sized screen and QWERTY keypad on the receiver. The front panel of the receiver also has connectors for standard printer port, serial ports, external monitor and external keyboard.

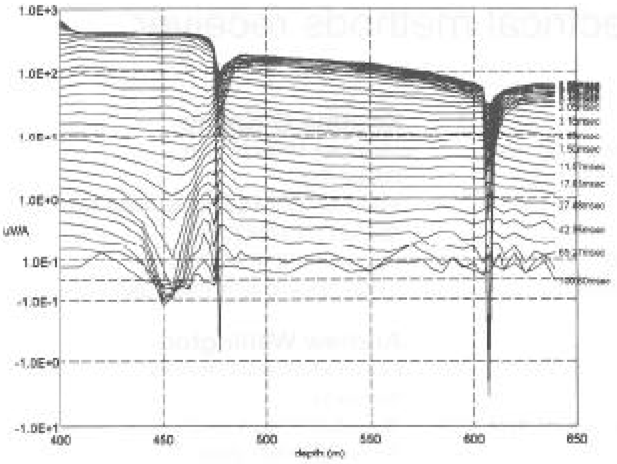

Figure 2. Profile of TEM data from a surface borehole near Coronet Mine, Kambalda. This borehole intersected massive NiS at 480 metres and a conductive metasediment at 619 metres.

(i) providing functions to automatically recognise and remove interference from data, especially cultural noise in the vicinity of mine sites and built-up areas;
(ii) supplying graphical evidence of signal and data quality to the instrument operator, and
(iii) serving as an easily programmable platform for the research and development of new data acquisition and processing methods.

As a result this instrument has the capability to record up to eight channels of data simultaneously in a fully programmable environment. Data acquisition is entirely under the control of software written in a high-level language to operate under Windows. Hard and floppy disk drives hold and transfer data and a VGA LCD monitor displays profiles, decays, spectra and waveforms. Oscilloscope and spectrum analyser functions are implemented.

The main aim of this paper is to illustrate the performance of the SMARTem instrument in a variety of environments. Several SMARTem data sets from base metal exploration at Kambalda, Leinster, Honeymoon Well and Mount Isa are presented here as examples and are used in the discussion of the functionality of this instrument.

The common practical problems faced during these surveys include:
(i) electrical interference from mine site infrastructure;
(ii) limited time allowed for the completion of surveys, and
(iii) extremely small signals from target conductors.

KAMBALDA & LEINSTER, WESTERN AUSTRALIA

Electromagnetic geophysical methods are an important tool in WMC Resources' exploration for nickel around Kambalda and Leinster in Western Australia. The most commonly utilised geophysical techniques are borehole and moving loop TEM.

Small, rich pods of nickel ore in close proximity to existing mine workings are valuable targets. In addition, 'grass roots' exploration, using TEM and other electrical methods, across mining and exploration leases in the Kambalda and Leinster regions aims to locate fresh nickel resources. Several data sets collected with a SMARTem receiver by WMC Resources as part of this work are presented here.

Figure 2 illustrates a logarithmic profile of SMARTem TEM data collected in 1998 at the bottom of a vertical surface borehole near Coronet mine, Kambalda. A 200 x 200 metre single turn transmitter loop at the surface was used in standard 50% duty cycle operation with a current of 22 A (Zonge GGT-30 transmitter) and base frequency of 2.083 Hz. The borehole collar is inside the transmitter loop, adjacent to its southern edge. Data was collected at forty-five stations in the hole between depths of 400 and 650 metres, in some cases using spacings of 2.5 metres. An MCI axial-component borehole TEM coil probe with an effective area of 10,000 m^2 was used as the receiver antenna and data are presented in units of microvolts per Amp.

A 5cm thickness of massive nickel ore was intersected at 480 metres depth in this borehole at the boundary between basalt and ultramafic lithologies. The other response shown is due to a conductive metasediment intersected at 613 metres. Modelling of the upper anomaly suggests a 30 x 30 metre conductor, dipping west at 50°, approximately centred on the hole (Elders, pers. comm.).

Total time taken to complete the log was 85 minutes, a rate of less than 2 minutes per station – this has become typical for Kambalda where a large volume of borehole TEM data is collected every year. One hundred and twenty eight transients, or 64 'stacks' in the common usage nomenclature, were collected at each position. Measurement time at each position is around 40 seconds with the remaining time used for viewing of the results, in profile or decay form, by the operator and winding the probe to the next position. In most cases borehole TEM surveys are carried out either immediately after, or during, drilling to ensure that full TEM logs are obtained prior to any collapse.

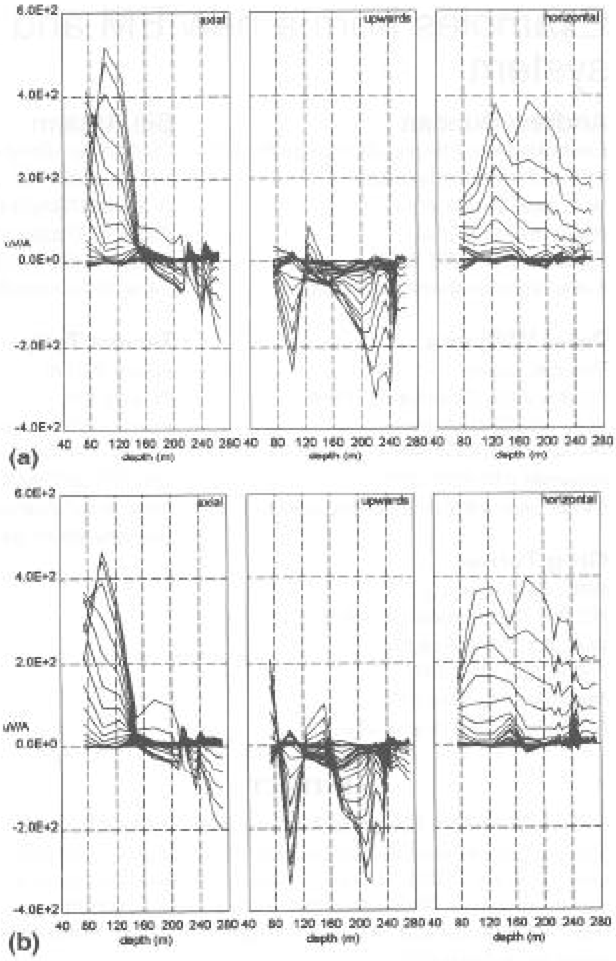

Figure 3. Profiles of 3-component TEM data from a surface borehole near Miitel Mine, Kambalda using (a) Geonics BH43-3D probe (b) Monash University VECTEM probe. Windows with delays from 1.8 to 115 milliseconds are shown. Left plot is A component, centre is U component, right is V component.

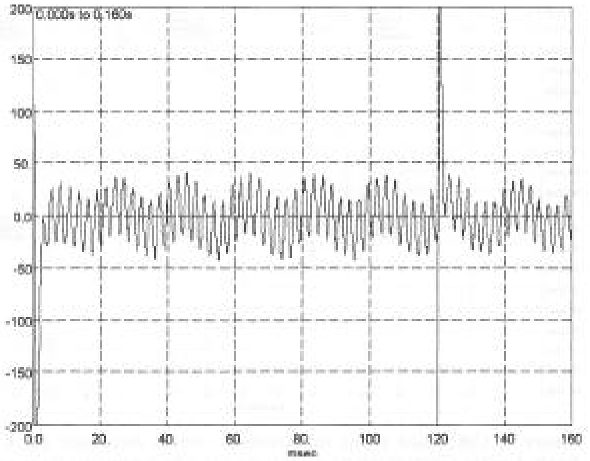

Figure 4. Raw time-series from surface borehole TEM survey at Leinster. Note primary field spikes, 50 Hz and mine communication system. Vertical scale 50 millivolts per division, horizontal scale 20 milliseconds per division. Data collected at depth 95 metres.

Some SMARTem surveys have been undertaken at Kambalda using 3-component borehole TEM probes. Geonics BH43-3D and Monash University VECTEM probes have been used at Kambalda recently by WMC Resources. Of the commercial 3-component TEM logging systems, almost all measure one component at a time and must be switched between components. Software was written for SMARTem to allow automated surveying with these probes. Upon initiation of a measurement, SMARTem measures/reads the angle of rotation of the probe and then records data on the three components, switching between them under software control. Finally, it applies a coordinate rotation to the transverse components and displays profiles in a reference frame fixed to the borehole.

A 3-component TEM data set from a borehole near Miitel Mine, Kambalda, is presented as profiles with linear vertical scales in Figures 3a (BH43-3D) and 3b (VECTEM). These surveys were done on the same day. The borehole was logged from a depth of 75 metres to 265 metres in both cases. It has an inclination of 60° at the collar and is drilled through metasediments into ultramafics and basalt. This borehole and loop are discussed in Elders and Wellington (1998). An intersection of 0.2 metres of disseminated sulphides occurs at 220 metres and 0.7 metres of massive sulphide is intersected at 246 metres. Current used was 2.8 A at 2.083 Hz in a 200 x 200 metre loop with closest edge 150 metres from the collar. Responses at delays from 1.8 milliseconds to 115 milliseconds are plotted. Data collected during these surveys suffered from mild 50 Hz interference and vibration from a diamond drill rig operating 40 metres away.

In each plot, axial-component (A component, uphole by convention) data is displayed in the left profile, U component (upwards in the vertical plane containing the drill hole, perpendicular to A) data is in the central profile and V component (horizontal, forming a right-handed orthogonal axis set U, V, A) is in the right profile. Responses are presented in microvolts per Amp and have been normalised to an effective coil area of 10,000 m^2 for each component because actual effective coil areas vary. As with the data shown in Figure 2, only 64 stacks were collected for each component to increase productivity. The anomalous zones at the base of the hole are clearly defined on all components.

Figure 4 shows a borehole TEM time-series with interference from power transmission lines and a common underground mine communication system called PED

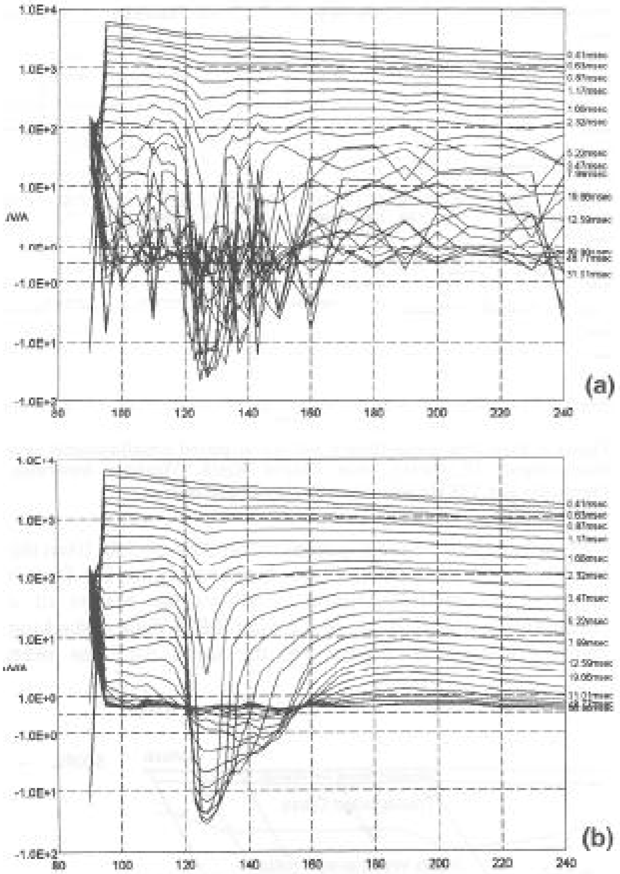

Figure 5. Profiles of TEM data from surface borehole at Leinster. Interference from PED system evident in (a) has been removed by processing, resulting in (b) which shows a well-defined off-hole anomaly.

(Personal Emergency Device). This data was collected in the vicinity of an operating WMC Resources nickel mine at Leinster, Western Australia at a base frequency of 2.083 Hz and a transmitter current of 29 A into a 2 turn 200 x 200 metre loop. Data is viewed in this 'oscilloscope' format on the screen of the SMARTem. The time-series shows the time variation of the voltage on the borehole receiver coil over 160 milliseconds at a vertical scale of 50 millivolts per division. It shows the switch-on (start of the series) and switch-off transients from the transmitter, 50 Hz sinusoids (20 millisecond period) and sinusoidal interference from the communication system (approximately 375 Hz = 2.67 millisecond period). In this example an MCI axial-component probe was employed.

The power transmission interference at 50 Hz is removed during processing mainly by the choice of an appropriate base frequency for the TEM survey and by the application of a tapered stacking scheme that has superior rejection of harmonic noise than a conventional stack. Removal of the PED interference is more difficult because its carrier frequency continuously varies over a range of 40 Hz (it is a frequency-modulated communication system). Without a filtering approach specific to the problem there is no chance of attenuating this 50 millivolt peak-to-peak noise to levels that are consistently achieved in surveys away from such interference. This PED interference is removed by a digital notch filter, applied during the survey or subsequently, that removes the affected parts of the signal spectrum and reconstructs them by extrapolation from the adjacent unaffected frequencies. This filter operates with the full on- and off-time stacked waveform for optimal performance.

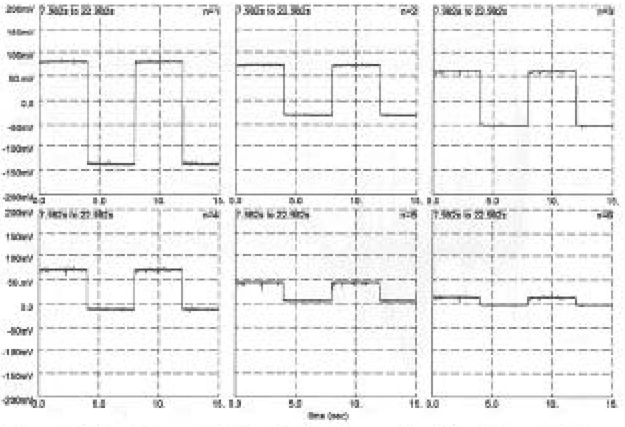

Figure 6. Raw time-series from 6 n-levels acquired simultaneously in a dipole-dipole IP survey near Mount Keith, Western Australia. Frequency is 0.125 Hz with an a-spacing of 100 metres.

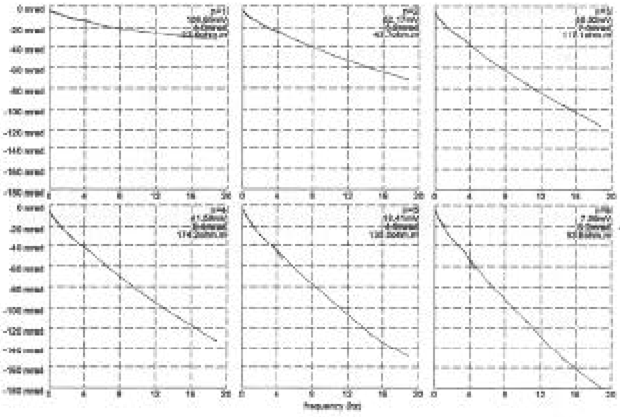

Figure 7. Calculated phase (milliradians) versus frequency for 6 n-levels. Curves constructed by overlaying five odd harmonics from each of 0.125 Hz, 0.5 Hz and 2.083 Hz. Larger phases at higher n-levels illustrate EM coupling responses.

Figures 5a and 5b are logarithmic profiles of data from the same borehole at Leinster. Data shown in Figure 4 is from a depth of 95 metres. Figure 5a shows the results of a conventional approach to processing TEM data – stacking and windowing. In Figure 5b, the same data has been filtered to remove PED with an obvious improvement in quality to show an off-hole anomaly.

SMARTem systems have been used mainly in the collection of TEM data; however, additional software modules are used to collect other styles of electrical geophysics data on up to eight channels concurrently. Some frequency domain IP work has been carried out in the Mount Keith area, north of Leinster. Figure 6 shows raw time-series acquired simultaneously from six dipoles in a dipole-dipole IP survey with an a-spacing of 100m. The time-series from n=1 to n=3 are plotted on the top row and n=4 to n=6 along the bottom. The plots show the voltages on each dipole resulting from the 100% duty cycle square wave transmitter current at a frequency of 0.125 Hz.

Figure 7 shows plots of phase versus frequency for the same dipole-dipole spread position as Figure 6. In Figure 7, the phases of five harmonics at each of three frequencies have been overlaid to illustrate the variation in phase over a frequency range 0.125 to 18.7 Hz. The increase in magnitude of phase response at higher n-levels, which is a result of EM coupling, is plotted for the instrument operator in this form to allow an unambiguous visual evaluation of data quality. The extrapolation of phase back to DC to derive the IP value is more likely to be affected by survey noise at the higher n levels where signal levels are smaller field plots of phase versus frequency at high n-levels are therefore useful quality control tools.

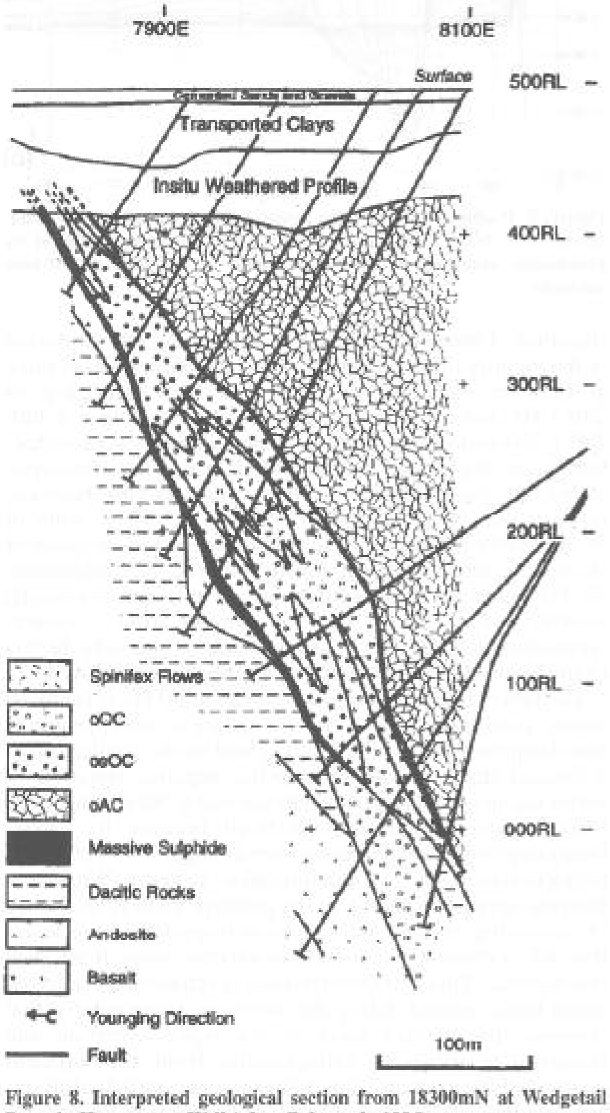

Figure 8. Interpreted geological section from 18300mN at Wedgetail Deposit, Honeymoon Well (after Gole et al., 1996).

HONEYMOON WELL, WESTERN AUSTRALIA

Honeymoon Well in the Agnew-Wiluna greenstone belt of Central Western Australia is the location of a number of significant disseminated and massive nickel sulphide deposits. The Wedgetail deposit, at Honeymoon Well, has been a popular site for tests of electrical geophysics instrumentation, particularly TEM (Bourne, 1996).

Wedgetail is a very conductive massive sulphide lens striking roughly grid north-south and dipping approximately 60° to grid east (Gole et al., 1996). It contains an estimated 2.5 Mt of ore at 3.36 per cent Ni. It has an 80 metre thick conductive cover of transported and weathered material (approximately 1 S/m conductivity) as shown in Figure 8 (section at 18300mN, taken from Gole et al., 1996). This deposit is difficult to detect with surface TEM because of the overburden thickness and conductivity. Tests carried out by CRA in 1993 demonstrated that measurement of signal was required at delay times in excess of 150 milliseconds to detect Wedgetail using 200 metre moving loop TEM. This was achieved using a proprietary receiver coil with large

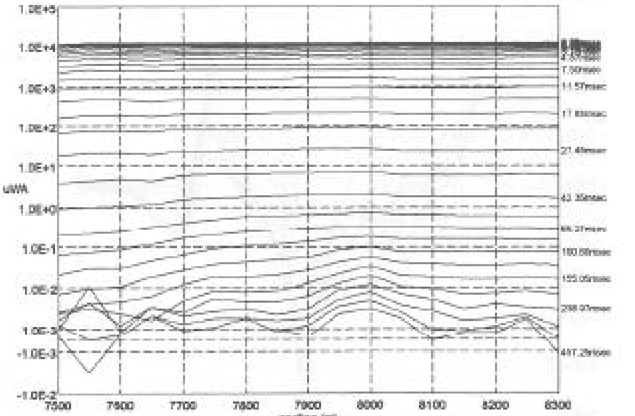

Figure 9. Profile of in-loop TEM data from 18450mN at Wedgetail. Survey used 3 turn 100 metre loops with current of 16 A and base frequency 0.4 and 0.5 Hz. Late-time response peaking at 8000mE is the Wedgetail deposit.

active area, a double turn transmitter loop and current of the order of 20 A.

During 1997, several new TEM surveys were carried out by Outokumpu Mining Australia over the Wedgetail deposit in the same location as previous test work. Equipment used was a SMARTem receiver, Zonge 10 kVa transmitter and a vertical axis receiver coil developed by Outokumpu. The circular receiver coil has a large active area, is 1 metre in diameter and portable. It has an effective area of 10,000 m^2.

New moving-loop TEM data from 18450mN is displayed in Figure 9 in a logarithmic profile – this northing is close to the section in Figure 8. This data was collected with 3 turn 100 x 100 metre transmitter loops, 16 A current and 50 metre moves. The receiver coil at loop centre was connected via umbilical to the receiver at a loop corner. Base frequencies of 0.4 and 0.5 Hz were used and several repeat readings of 128 stacks were taken at each station. An anomaly peaking at 8000mE is evident to the east of the projected surface intersection of the Wedgetail deposit.

This response begins to distinguish itself from the background at a level of 0.1 microvolts per Amp and at a delay of less than 100 milliseconds, however the collection of data to delays in excess of 250 milliseconds was critical in clarifying the anomaly. At the longest delays, background responses were around 0.001 microvolts per Amp or 1 nanovolt per Amp. The response at 8000mN at the longest delay (457 milliseconds) is 3 nanovolts per Amp. A comparison of decays from stations 7900mE, 8000mE and 8100mE is given in Figure 10 in a log-linear plot of response versus delay time. A comparison of the previous 200 metre moving-loop TEM data (collected by CRA Exploration, not shown) with this 100 metre data shows that the Wedgetail response can be observed earlier in delay time with the smaller transmitter loop. Modeling with CSIRO's Leroi software confirmed that this result is to be expected in this case. As a result, smaller transmitter loops are being employed in further exploration, with somewhat higher base frequency.

Fixed-loop TEM data was collected using the same transmitter unit, receiver coil and vertical axis receiver. A 200 x 200 metre transmitter loop was sited with western edge above the top of the Wedgetail deposit at 7900mE. One line was surveyed through the centre of the loop at 18450mN. Transmitter current was 24 A through a single turn with a base frequency of 0.4 Hz. Results are presented in a logarithmic profile in Figure 11.

The time behaviour of the cross-over to the west of the loop indicates that a localised conductor exists beneath the conductive cover. At short delays the cross-over is clearly associated with the transmitter loop and it eventually starts migrating outward on both sides of the loop. At delays approaching 500 milliseconds, however, the western cross-

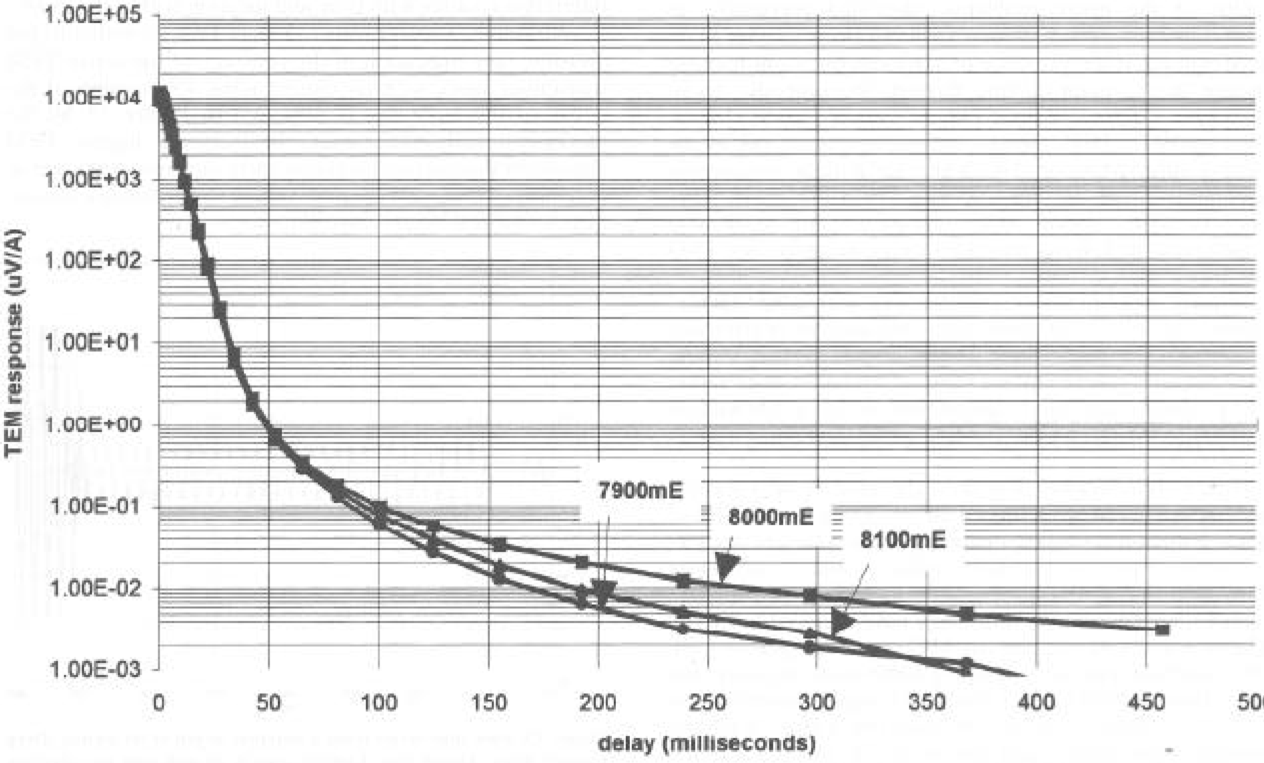

Figure 10. Decays from stations 7900mE, 8000mE and 8100mE of Wedgetail in-loop survey on 18450mN. Anomaly at 8000mE becomes clear at around 100 milliseconds but longer delays are important in its definition.

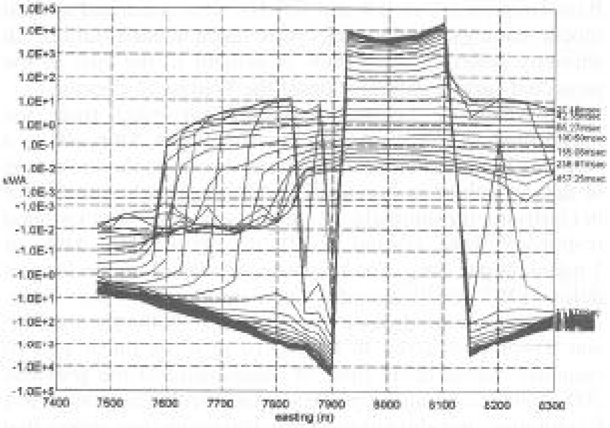

Figure 11. Profile of fixed-loop TEM data from 18400mN at Wedgetail. Survey used a single turn 200 x 200 metre loop with edges at 7900mE and 8100mE. Base frequency was 0.4 Hz and vertical axis measurements were made through the loop centre. The Wedgetail deposit responds as a late-time cross-over at 7830mE.

over has been drawn back in to 7830mE, close to the projected surface intersection of the Wedgetail deposit. As expected, responses are in general somewhat larger than in the 100 metre moving-loop data. Modelling of the late-time fixed-loop response using a simple filament model shows that it almost certainly results from Wedgetail.

MOUNT ISA, QUEENSLAND

During 1997 and 1998 borehole TEM surveys have been carried out with SMARTem systems underground in the vicinity of the Deep Copper Orebody at Mount Isa Mine in north-western Queensland. Aims of these surveys were to: (i) develop a technique to yield high quality borehole TEM results in a noisy underground environment (ii) explore the footwall of the 3500 Copper Orebody.

One of the major problems, identified previously, in performing effective EM surveys in the Deep Copper Mine at Mount Isa is the presence of a Kiruna truck ore haulage system in the main decline through the orebody. These trucks are electrically driven on a series of overhead rails. Prior to 1997, TEM surveys were only carried out in the Deep Copper Mine on days when the Kiruna system was decommissioned for maintenance. In 1997 these days became unscheduled and infrequent. An additional impediment to EM surveys, introduced recently, is a PED communication system.

In early 1997 trials were undertaken with a SMARTem receiver to collect raw time-series and analyse interference problems. The trials were implemented by the Mining Research group at Mount Isa Mines. As a result, exploration TEM surveys are now carried out using a SMARTem receiver in the Deep Copper Mine while the Kiruna system is operating.

Figure 12 shows a linear scale profile of borehole SMARTem TEM data logged in the Deep Copper Mine while Kiruna trucks were operating in the adjacent decline, 10 metres from the borehole collar. A 300 x 300 metre horizontal underground transmitter loop was used for this survey with a current of 12 A and a base frequency of 1 Hz. The receiver antenna was an MCI axial-component coil. The borehole dips at 36° to the north-east, intersects the west-dipping 3500 Copper Orebody (copper mineralisation of 1.5% or more between 169 and 198 metres depth) at roughly right angles and continues 70 metres into the footwall. Only windows from delays longer than 20 milliseconds are shown in Figure 12; earlier, narrower

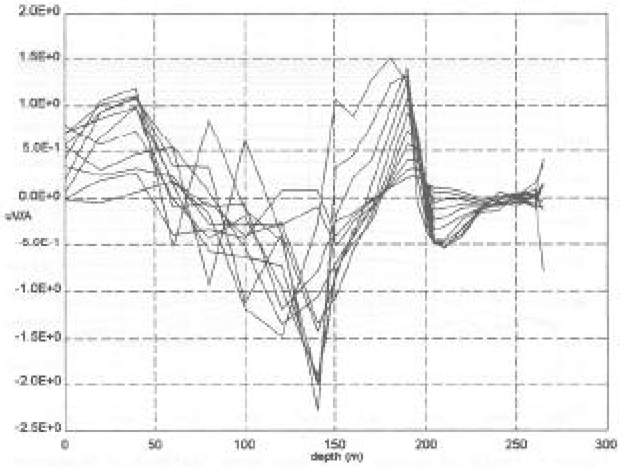

Figure 12. Profile of TEM data from underground borehole in Deep Copper Mine at Mount Isa. Late-time windows from 20 to 200 milliseconds delay are shown. This borehole intersects the 3500 Cu Orebody between 169 and 198 metres.

windows have poorer signal-to-noise ratio and have been deleted to make this figure clearer. Note that all TEM responses in this borehole, including those at the early times not shown, have magnitude less than 2 microvolts per Amp over the entire borehole, which is considered to be quite small. No new conductors are observed in the footwall of the 3500 Orebody at this location.

Figure 13 illustrates a raw time-series recorded during the survey. It shows the interference from a Kiruna truck climbing the decline and crossing from one segment of the overhead power distribution network to another. This example is from a measurement at a depth of 60 metres in the borehole. The interference is dominantly 50 Hz but is strongly contaminated with harmonics. The nature of the interference varies with time and location within the mine.

Note that the vertical scale in Figure 13 is 20 millivolts per division. Any indication of the presence of the active TEM transmitter loop, with its closest edge 400m south of the collar of the borehole, is obscured in Figure 13 by the aforementioned interference. In fact, the largest TEM signals for this survey, including early time responses, are of magnitude 20 microvolts, approximately 3000 times smaller than the largest interference shown.

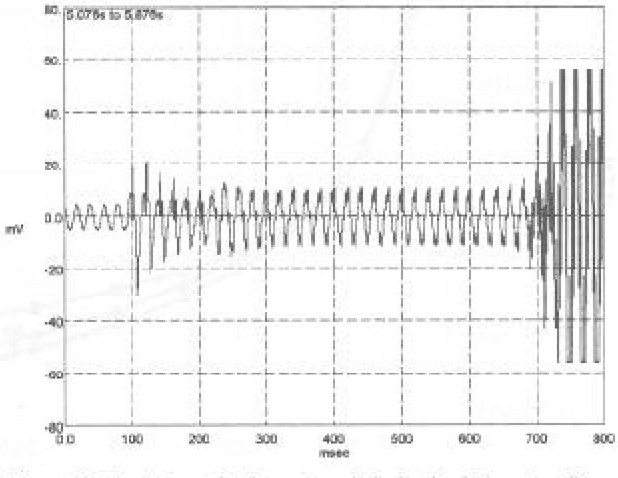

Figure 13. Raw time-series from a borehole depth of 60 metres (Deep Copper Mine, Mount Isa). Vertical scale is 20 millivolts per division, horizontal scale is 100 milliseconds per division. Interference from electric trucks travelling on adjacent decline is shown.

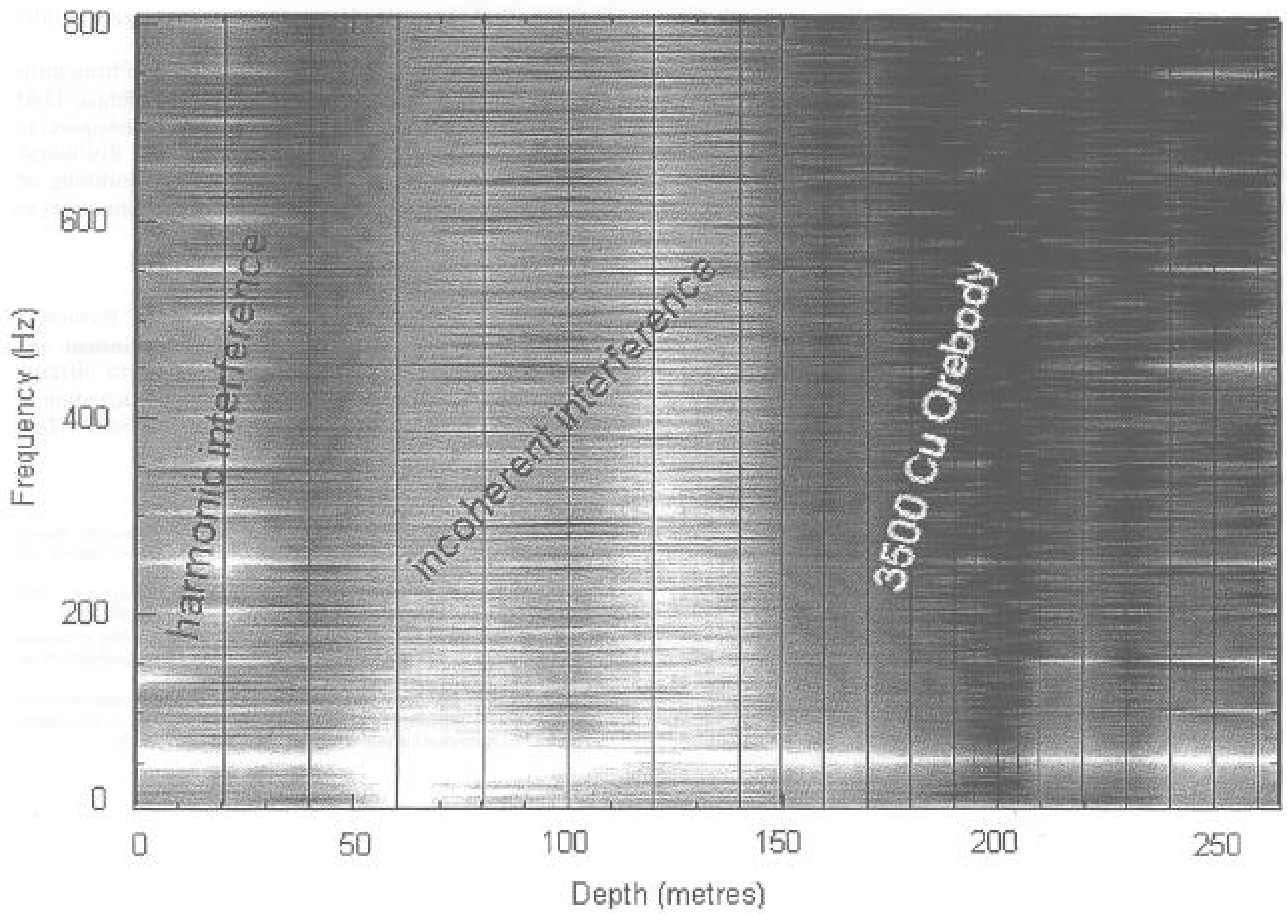

Figure 14. EM interference in borehole (Deep Copper Mine, Mount Isa) gridded as a function of frequency and depth. The 3500 Orebody (intersected between 169 and 198 metres) appears as a zone where only low frequency interference is detected.

The data plotted in Figure 12 is a result of between 128 and 256 stacks per station, with an improved stacking scheme and use of the receiver's oscilloscope functionality to assess the changing interference levels. Anomalously noisy readings and readings where there were large changes in the character of noise were cancelled by the operator and repeated prior to moving the probe to the next station.

Figure 14 comments graphically on the nature of interference in this borehole TEM survey and uses it in a simple way to infer the location of the 3500 Orebody. This figure shows the noise spectrum gridded as a function of depth down the borehole. The spectrum at each depth was calculated using raw time-series recorded during the survey. The resulting image in Figure 14 has been histogram-equalised. White represents the highest noise and black represents the lowest. The vertical black lines show the location of measurements. Noise at 50 Hz is present along the entire borehole but strongly attenuated inside the 3500 Orebody. The first 150m of the hole shows quite broadband noise character, with noise at the first two stations, closest to the decline, dominated by harmonics of 50 Hz. The strongest attenuation of interference is near 200 metres depth, at the base of the 3500 Orebody intersection.

The TEM data set has been transformed to an effective B-field measurement and plotted in Figure 15. This transformation is an integration with respect to time, the aims of which are to enhance the response of highly conductive features and to reduce the effect of high frequency noise (integration is a low-pass frequency filtering operation) on interpretation. Figure 15 has the same range of window times, 20 milliseconds to 250 milliseconds, as Figure 12 and they can be directly compared. The units used in the display of the transformed data are nanotesla per Amp.

Clearly the transformation to B-field has improved the interpretability of the TEM profiles, especially in the region between 50 and 150 metres depth where higher frequency noise had affected the quality of the dB/dt data. In this case the process of transformation from dB/dt to B responses has used the full on and off-time waveform. Integration by simple calculation of the area beneath off-time dB/dt curves

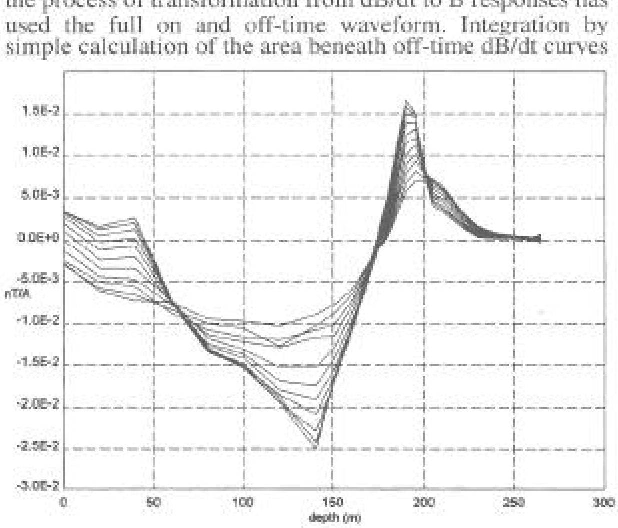

Figure 15. Profile of B-field borehole TEM data calculated by integrating full waveform dB/dt data. Late-time windows from 20 to 200 milliseconds delay are shown. Compare to figure 12. B-field response of 3500 Orebody is clearer than comparable dB/dt as a result of the slow decay of target compared with host response.

does not resolve constants of integration required for accurate B-field transformations.

DISCUSSION

Data sets acquired with the SMARTem receiver at Kambalda, Leinster, Honeymoon Well and Mount Isa have been presented. This data has demonstrated the functionality of the SMARTem receiver system in performing EM and IP surveys, manipulating raw time-series, reducing the effects of interference and using novel approaches to process signals.

At Kambalda and Leinster in Western Australia, where SMARTem systems have been used extensively in exploration by WMC Resources, because of interference from power transmission and communications equipment, processing algorithms have been developed by the instrument manufacturers to remove interference to levels where it does not hinder interpretation. In addition, graphical feedback to the receiver operator allows surveys to proceed quickly with a high level of confidence in data quality. The IP functionality of the SMARTem receiver system has been illustrated.

At Honeymoon Well's Wedgetail deposit, a target difficult to detect geophysically, TEM signals of magnitude 1 nanovolt per Amp and less have been measured routinely with a SMARTem as part of exploration work using a new vertical axis receiver antenna. Results of experimental work have been used to implement more efficient surveying techniques in the exploration for targets similar to Wedgetail.

In Mount Isa's Deep Copper Mine interference from mine infrastructure is significant and deleterious to borehole TEM surveys. Examples of interference and techniques to attenuate its impact on interpretation are discussed. These include signal processing, constant monitoring of signal quality and transformation of dB/dt measurements to B-field.

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