Environmental Site Assessment at a Mining Operation in Western Australia Using the Loupe TEM Profiling System

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SUMMARY

The Loupe TEM is a transient electromagnetic profiling system for efficient mapping of near-surface ground conductivity. The system is operated by a two-person crew who carry the transmitter coil and 3-component receiver coils on backpacks. Benefits of the system include the high productivity and the ability to survey in various types of terrain and through dense vegetation.

In mid-2020, we utilised the Loupe TEM system in the Pilbara region of Western Australia to investigate potential fluid pathways and contamination around an environmental pond. A total of 23.5 km line kilometres of data was acquired on a dense grid with 20 m line spacing. We used a 75 Hz base frequency and stacked 300 transients to improve the signal-to-noise ratio. Data were gridded to highlight spatial features and modelled to create conductivity depth images. Supporting information included a frequency-domain EM survey using Geonics EM-34 equipment, passive seismic data obtained using the Sara GeoBox, and information from groundwater monitoring bores.

The results identified various laterally coherent zones with elevated electrical conductivities, some of which related to or appeared to originate from the environmental pond. Features of interest included a shallow clay layer, a likely bedrock shear zone, and possible contamination. The Loupe TEM data correlated well with EM-34 bulk conductivity values, while passive seismic data provided useful supplementary information on bedrock depth. Groundwater sampling data did not always correlate with EM survey results, but without conclusive evidence as to the cause of the discrepancy.

Key words: transient electromagnetics, environmental, groundwater

INTRODUCTION

Electromagnetic (EM) geophysical methods are frequently used for environmental investigations thanks to their ability to investigate conductivity variations induced by differences in texture, saturation and fluid properties. However, when conducting site investigations, one often needs to find a trade-off between depth of investigation, detail of information, and survey efficiency of different survey options.

Frequency-domain EM (FDEM) systems collect continuous-mode data without ground contact, but the resulting bulk electrical conductivity data offer limited depth information. FDEM systems that use multiple or variable loop orientations and separations are often either rather inefficient or challenging to operate due to their large weight.

Time-domain EM (or transient EM, TEM) methods afford good depths of investigation and their data can be used to create models of the subsurface conductivity distribution. However, the standard ground-based moving loop approach is relatively inefficient.

To improve data acquisition efficiency and to obtain higher-resolution data, various ground-based TEM profiling systems have been developed in recent years. This includes towed systems that can achieve significant depths of investigation but require track access or open ground (e.g, Hatch et al., 2010; Allen, 2019; Auken et al., 2019). The new operator-carried Loupe TEM system (Duncan and Street, 2019) is more mobile than ATV- or vehicle-towed systems but has lower depths of investigation.

In this article, we discuss a recent project where we used the Loupe system for an environmental site investigation in the Pilbara region of Western Australia. We discuss survey objectives, methods and survey design, data processing and modelling, and results.

APPROACH

Loupe TEM system

Loupe is a portable TEM profiling system, with the transmitter and receiver carried by separate operators. The system is designed to be used in continuous profiling mode with a variable transmitter-receiver separation (Street et al., 2018). Datalogging and track guidance is handled by a field tablet that is wirelessly connected to the data acquisition system in the transmitter backpack.

The most recent version of the Loupe system has a transmitter (Tx) coil with 13 turns with an effective area of 4.538 m^2. With a current of 20 A, the Tx has a maximum moment of 90.76 Am^2. The Tx operates at selectable base frequencies from 25 to 150 Hz and uses a 50% duty cycle to produce a bi-polar square waveform. Signal switch-off takes approximately

8 µs. At the standard Tx repetition rate of 75 Hz, one full cycle of the transmitter waveform takes 13.33 ms.

The receiver (Rx) is a 3-axis coil with a common centre point and effective areas (after amplification) of 200 m^2 (Duncan and Street, 2019). The Rx sensor has a 100 kHz bandwidth using a sampling rate up to 504 kHz. Receiver gain can be varied depending on transmitter-receiver separation. Signal voltages are recorded and processed to 22 logarithmically spaced time windows, with the first and last at 0.006 and 2.27 ms from the end of the ramp, respectively, for the 75 Hz transmitter base frequency.

In its current design, a cable passes analogue signals from the receiver sensor to the data acquisition electronics in the transmitter operator's backpack. To avoid electromagnetic interference, the receiver backpack currently has no data acquisition electronics. Development aimed at placing the data acquisition unit and a second GPS antenna in the receiver operator's backpack is ongoing.

Loupe data pre-processing typically includes stacking and filtering to attenuate noise caused by operator movement, followed by windowing. Data are then corrected for system response. The typical stack includes two seconds of data, which at a transmitter base frequency of 75 Hz, equates to 150 full signal periods. Stacked data are output at user-selected intervals with or without overlap between stacking windows. A common output is one reading per second. At a typical walking pace of around 3.7 km/hr, this results in approximately one reading per meter. The final pre-processing step is the application of a parallax correction to calculate the central point half-way between transmitter and receiver loops.

Post-processing and visualisation of the Loupe data typically starts by gridding the ground response data for different times after signal shut-off. To obtain variations in electrical conductivity with depth, conductivity depth images (CDIs) or inversion models can be generated using appropriate software (van Dam et al., 2020).

Case study

In mid-2020, we conducted a geophysical survey at a mining operation in the Pilbara region of Western Australia to investigate the area around a facility for storage of overflow processing water during high rainfall events. The assumption was that seepage or fluids from overtopping events might be present outside the pond area. Evaluation of existing groundwater sampling data at the site showed that seepage would likely be associated with elevated bulk electrical conductivities values. A Geonics EM-34 frequency-domain EM survey conducted several years prior had identified various areas of interest.

The primary objective of the site investigation was to map spatial and vertical variations in ground conductivity potentially caused by the presence of contaminated soils and groundwater, and by seepage in bedrock shear and fracture zones. A secondary objective was to estimate the depth to fresh bedrock. The crystalline granitic bedrock was believed to have a limited weathering profile at a depth of 3 to 5 m below a clayey or silty overburden. Overburden thickness above bedrock shear and fracture zones would possibly be greater. Open-file airborne VTEM data indicated that bedrock in the region was generally highly resistive.

The Loupe TEM profiling system was used to map spatial variations in ground conductivity on a dense grid with a 20-m line spacing of (Figure 1). The transmitter-receiver separation was kept at approximately 12 m for the duration of the survey.

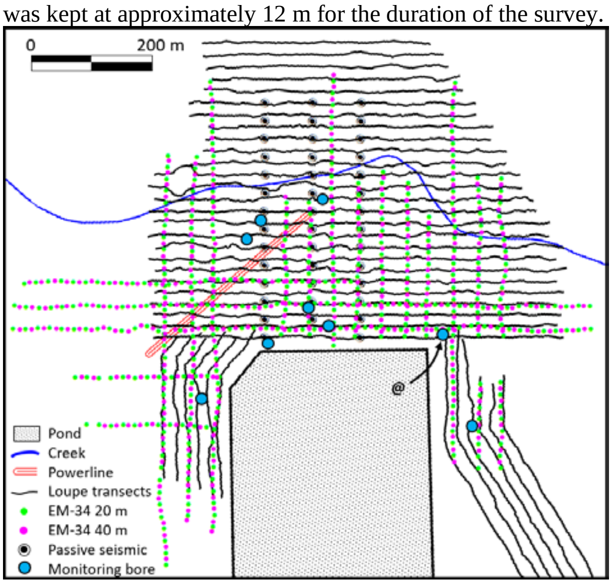


Figure 1. Survey area showing site features and locations of geophysical measurements. Approximately 18 km of the Loupe TEM transects is shown in this map. The EM-34 stations shown are for the VCP loop orientation. The powerline leads to permanent equipment near the creek.

We used a pulse repetition rate of 75 Hz. In total, 23.5 line kilometres of data was acquired in 2 days. Parts of the site were heavily vegetated, but apart from occasional small detours, the Loupe survey lines was completed as planned.

Complementary passive seismic data for depth-to-bedrock estimates were collected at 39 survey stations (Figure 1). When a strong impedance contrast is present in the subsurface, for example at the bedrock transition, the vertical and horizontal components of the ambient noise field in the overburden will differ. By converting a time series of ground motion to the frequency domain and calculating the horizontal-to-vertical spectral ratio (HVSR), the resultant resonance frequency can be related to depth of the contrast (e.g., Lane et al., 2008). We used 3-component Geobox seismometers from SARA Electronic Instruments and processed the data using SARA's GeoExplorer software.

In mid-2012, a geophysical survey was conducted using a Geonics EM-34 frequency-domain EM system. During the 4 days of surveying, data were acquired using 20 and 40 m loop separations, both in vertical co-planar (VCP) loop orientations (horizontal dipoles) at 430 and 413 stations, respectively, and in horizontal co-planar (HCP) orientations at a subset of 218 and 217 stations, respectively (Figure 1). Station spacing was 20 m while line spacing was approximately 40 m.

RESULTS

The gridded Loupe survey data showed strong lateral coherence (Figures 2a, 2b). Areas with elevated ground response are indicative of cultural features (e.g, the power line, visible at later times), higher soil electrical conductivities, increased overburden thickness, or other features of natural origin. In many cases, the areas of elevated signal response correlate very well with the EM-34 survey conducted in 2012

(Figures 2c, 2d). The powerline response is also clearly visible in the EM-34 data, in particular the readings with 40 m loop separation (Figure 2d).

A zone of shallow clay is clearly visible towards the right in Loupe's early time channels (Figure 2a) but is absent from later ones (Figure 2b), supporting the interpretation of a shallow conductive feature. The EM-34 data identified this feature in readings taken with the VCP orientation at 20 m separation, which have a depth of investigation of around 15 m. In the readings at 40 m separation (depth of investigation around 30 m), the signature had significantly weakened, although the survey direction may have been a factor. Some of this clay was subsequently dug up for use as lining material when upgrading the overflow pond; it is visible in the EM-34 data (Figure 2c), but not in any of the Loupe TEM channels.

Several of the areas with elevated signal response abut or are connected to the pond. Without supporting information, it was not possible to conclusively attribute these to overburden thickness variations, different soil properties, or the presence of contaminated fluids. However, one strong feature in the Loupe data was not present in similar form during the 2012 EM-34 survey. This feature starts near the top left corner of the pond and extends to and across the creek (arrow marked "#" in Figures 2a, 2b). It has a strong signature and remains visible to at least 1.3 ms after signal shutoff (time channel 12).

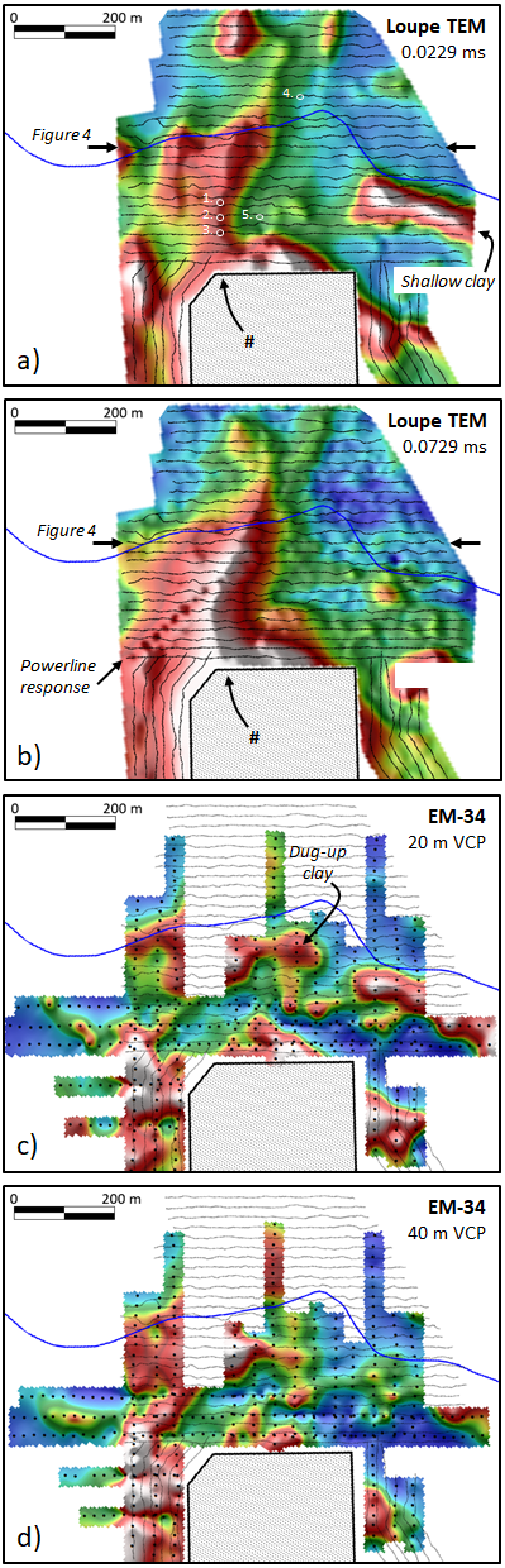
In 2012, the area near the creek also had higher conductivity values, but there was no connection with the pond. The development of this connection evident in the Loupe TEM data suggests that one or more overtopping events in intervening years caused migration of contaminated fluids from the pond toward the creek, possibly in a bedrock shear zone.

Horizontal-to-vertical spectral ratio (HVSR) analysis of the passive seismic data revealed a series of small but clear peaks (Figure 3) in a portion of the survey area where the Loupe data identified elevated soil conductivities. This suggests that this zone may have greater depths to bedrock or a sharper contrast in acoustic impedance values. In most other areas distinct peaks were absent, suggesting that depth to bedrock was too shallow to record a usable signal or that the overburden to bedrock transition was too gradual.

The HVSR resonance peaks generally had frequencies of around 2.5 to 3.3 Hz (Figure 3). Using a typical value for the shear wave velocity in dry, unconsolidated material of 200 m/s (e.g., Odum et al., 2007) bedrock depth can be calculated as around 15 to 20 m below ground surface. These values are higher than expected and investigative drilling would be required to confirm these results.

Groundwater sampling results did not always correspond to the Loupe survey data. For example, the bore marked "@" in Figure 1 contained water with a specific conductance of around 36,400 µS/cm around the time of the Loupe survey, but no elevated signal responses were recorded by the Loupe system. However, since the sample was retrieved from the bottom of the bore with an unknown screen length, at 22.5 m below ground surface it is not possible to conclusively attribute the mismatch to either the fluid or formation properties or to Loupe TEM limitations.

Figure 2. Maps of gridded EM survey data. The Loupe data for time channels 6 (a) and 10 (b) show the time after shutoff of the Tx signal in the top right corner. Yellow circles in (a) represent the locations of passive seismic readings with a clear HVSR peak. The EM-34 data (c, d) have Loupe transect locations overlain for reference.



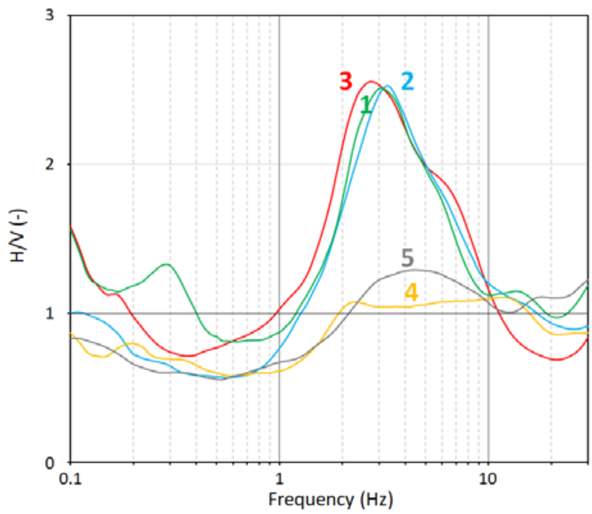


Figure 3. Horizontal-to-Vertical Spectral Ratio (HVSR) plots for 3 stations with a clear peak and 2 stations without (see Figure 2a for locations).

Loupe time-channel data are shown for a survey line with both elevated and low signal amplitudes (Figure 4a). The small peak in channels 1 to 5 at around 475 m distance (Figure 4b) is associated with the creek crossing. For the line segment from around 75 to 250 m distance, the elevated responses extend to later time channels (Figures 4a, 4b).

When plotted on a logarithmic scale, it is evident that signal decay in Z-component data is coherent to around time channel 10 (0.0729 ms) in resistive areas and around channel 12 (0.1333 ms) in conductive areas (Figure 4b). At amplitudes below around 1 µV/A the random noise increases significantly; the effect of this can be reduced by applying a low-pass filter. The horizontal X-component of the data displays more noise at early time channels. This is likely a result of the smaller signal amplitudes and more significant noise sources on horizontal component data.

The Loupe TEM data were processed using EmaxAir software developed by Fullagar Geophysics (Fullagar and Reid, 2001) to create Conductivity Depth Images (CDIs). At each delay time, t_n, the algorithm computes the apparent conductivity, σ_a, and then determines the depth to the current maximum at that time in a half-space of conductivity σ_a. In this way, n conductivity-depth pairs were generated at each station along the Loupe profiles (van Dam et al., 2020). Since for Slingram configurations, such as used by Loupe, σ_a of individual dB/dt components can be non-unique, we used the total field amplitude for processing (Schaa et al., 2006).

Example results of the transformation using the total field data are shown in Figure 4d. The zones of elevated electrical conductivity are clearly visible, with electrical conductivities up to around 100 mS/m. The conductive features correspond to confirmed locations of high-conductivity groundwater, with specific conductance values up to around 41,000 µS/cm recorded around the time of the Loupe survey. However, since the monitoring bores are screened over large vertical extents and no information about the stratigraphy or depth to bedrock was available it is difficult to use these data for a more quantitative comparison.

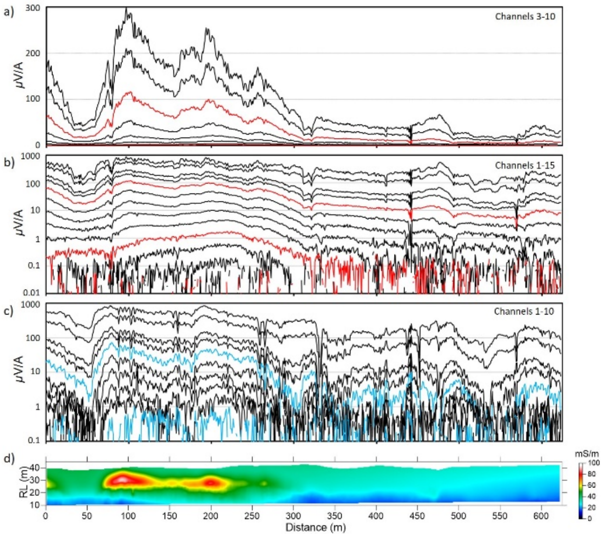


Figure 4. Loupe TEM Z- (a,b) and X-component channel responses (c) for the survey line indicated in Figure 2. Time channels 5 and 10 are coloured red and blue in (a) and (c), respectively. In (b), channels 5, 10, 15 are coloured red. Corresponding CDI model results (d), created using EmaxAir software for data from channels 3-13 (a 9-point moving average filter was applied to channels 8-13).

CONCLUSIONS

Profiling TEM systems allow for improved efficiencies in shallow conductivity mapping by using higher acquisition speeds while collecting feature-rich datasets. The Loupe TEM profiling system, which is operated by a two-person crew who carry the equipment on backpacks is highly mobile and can go virtually anywhere where a person can walk.

We utilised Loupe TEM at a mine site in the Pilbara region of Western Australia to investigate potential fluid pathways around a facility for storage of overflow processing water. We achieved a daily production of up to 12 kilometres despite, at times, dense vegetation. Time series data were gridded to visualize the lateral variations in electrical conductivity and compared with results from a Geonics EM-34 survey conducted several years prior. Data were transformed to conductivity depth images (CDIs).

The results identified various laterally coherent zones with elevated electrical conductivities, some of which were connected to the pond. The Loupe data showed excellent correlation with the EM-34 data, including in areas where shallow clay had been confirmed to exist.

One area where the Loupe TEM data differed from the EM-34 data was a feature that originated at the pond extending a few hundred meters to and across a small creek (dry during both visits). The presence of small but clear HVSR peaks in this area suggested greater depths to bedrock or a sharper contrast in acoustic impedance values. This feature may be a bedrock shear zone where the elevated conductivities suggest the presence of contamination as result of one or more overtopping events that would have occurred during the years in between the EM-34 and Loupe TEM surveys.

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