DEVELOPMENTS IN A NORMAL MODE HELICAL ELECTRICAL ANTENNAE CROSSOLE INSTRUMENTATION AND INTEGRATED INTERPRETATION SYSTEM

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Abstract

Electromagnetic crosshole methods are promising for imaging conductivity, permitivitty and permeability variations in the earth. Radio and radar frequencies with electric field antennae offer advantages for resolution and sensitivity in a wide range of environments. However, scattering difficulties created by small, near-field inhomogenities and attenuation issues have limited the use of such systems. Our modelling studies have indicated the usefulness of lower frequency antennae in a wide range of applications but antennae lengths and efficiencies under conventional design have prohibited application at this lower range. The use of normal mode helical antennae (NMHA) provides the opportunity to exploit a range of frequencies lower than those employed with conventional antennae design while retaining the resolution and sensitivity advantages of these techniques. We have found these lower frequencies are accessible using a NMHA system with the antennae providing acceptable efficiencies from a compact downhole device both in length and thickness. The broadband effectiveness of the NMHA allow for effective multi-frequency investigation with a single antennae.

In conjunction with instrument development, we have developed simulation capabilities both for the antennae radiation pattern and electromagnetic wave scattering in a three-dimensional environment allowing for contrasts in resistivity, electrical permittivity and magnetic permeability. A variety of useful data representation techniques have been developed to display data effectively in one, two and three dimensions. Useful tomographic techniques have been developed for the system allowing for near-field scattering and curved boreholes.

Survey techniques and data will be presented for several different types of applications. Data will be presented from a calibration site with detailed logs, a landfill site with leachate contamination, an industrial site with industrial cleaning solution contamination, and a survey to study groundwater geometry in a glacial till environment.

Introduction

In many situations, the use of either surface or surface to borehole electromagnetic techniques are restricted or provide insufficient resolution. For example, surface infrastructure or surface noise prohibits the use of such techniques. The size of the subsurface structures required to be detected can also limit the use of surface techniques. Although borehole or cross borehole radar systems can be used in some situations, the distance “seen” from the boreholes is limited. We wished to develop a system suitable from application to geotechnical, environmental and mine development applications.

The use of crosshole electromagnetic systems has long been considered potentially useful and developments have been carried for both electrical and magnetic antennae. With the use of modelling software, we were able to determine that for a range of applications electric field transmitters with electric receiving antennae offered sensisitivity advantages for a wide range of applications. Moreover, to reduce energy loss through attenuation and scattering from small objects, we determined that low radio frequencies would be desireable. Thus, we sought to develop a system which would enable us to work at frequencies between 100 KHz and a few megahertz.

Although such systems have been available with the use of traditional line antennae, their application has been restricted due to the required lengths of such line antennae at the desired frequencies. In addition, it was felt that to provide such equipment for use in geotechnical and environmental applications, the equipment should be relatively inexpensive and easy to use.

Antennae

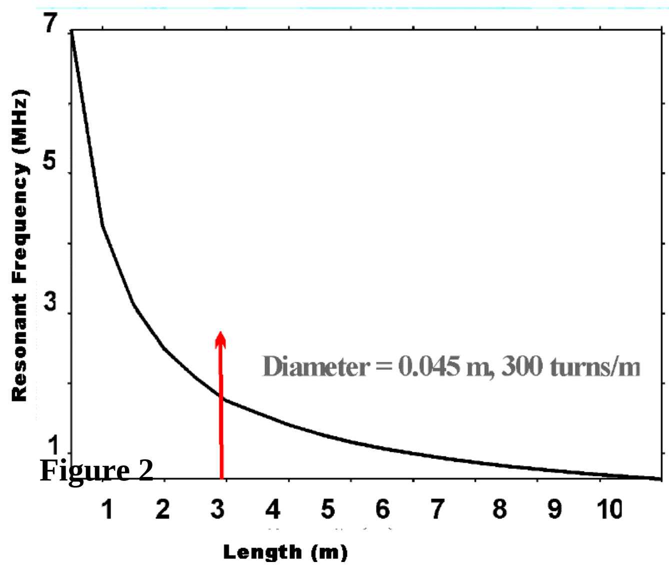


Figure 1: NMHA FreeSpace Resonance

Conventional one-eighth wavelength antennae design requires antennae lengths which are too long for most geotechnical and environmental holes and too long for detailed target resolution for mining applications. We considered a compact antennae design utilized in cell phones. These antennae are known as normal mode helical antennae which the requires the wrapping of conductive wire around a non-permeable core with radiation characteristics varying depending on diameter, number of turns, length and pitch.

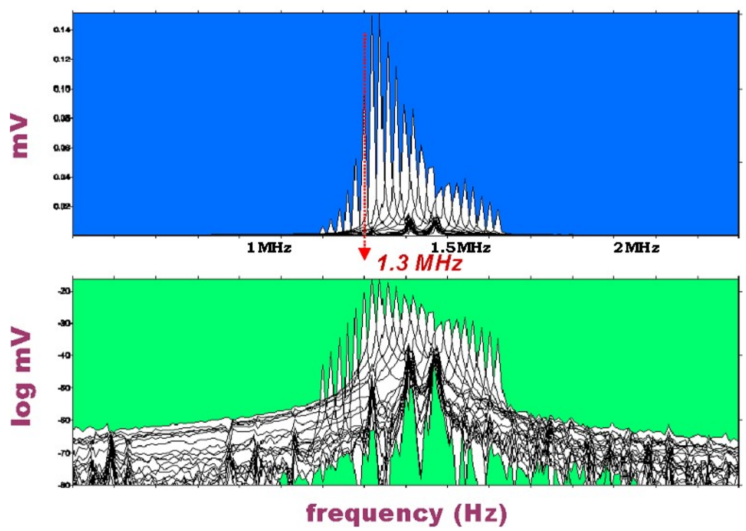
As an example, Figure 1 illustrates the variation in freespace resonance as a function of length with the diameter and number of turns held constant. One can see immediately the advantage in length over standard quarter wave or one-eighth wave antennae.

The red arrow in the figure shows our initial choice of antennae length. In practice, the antennae length was 3m utilizing 883 turns of wire for a total wire length of 125m. Figure 2 shows a picture of a pair of these antennae with the signal wave generator and data collection system in the back of the truck.

Figure 3 shows a series of spectra showing the resonance band in free air. In free air, we get a fairly rapid increase in reactance away from resonance with a corresponding loss of power.

Figure 2: Antennae and Acquisition System

Figure 3: Free Air Resonance Test



One remarkable aspect of the NMHA is that within earth materials, the efficient frequencies for radiation decrease from the freespace resonance frequency and the efficiency band widens often providing a fairly wide frequency band in which to perform our experiments. Figure 4 shows an example of the received power peak at about 500Khz in glacial till.

This aspect of the antennae to broaden their resonance characteristics within earth materials proved to be crutial to utilizing such antennae. Due to their effectiveness in picking up radio transmissions, we discovered that there is a great deal of noise in the radio band from a variety of unexpected sources. Also, the ability to work within a fairly broad frequency band allowed us to collect data at several frequencies with the same antennae.

In later work, a series of antennae were built for thinner holes and also shorter antennae (1.4m) to provide better resolution in very short holes.

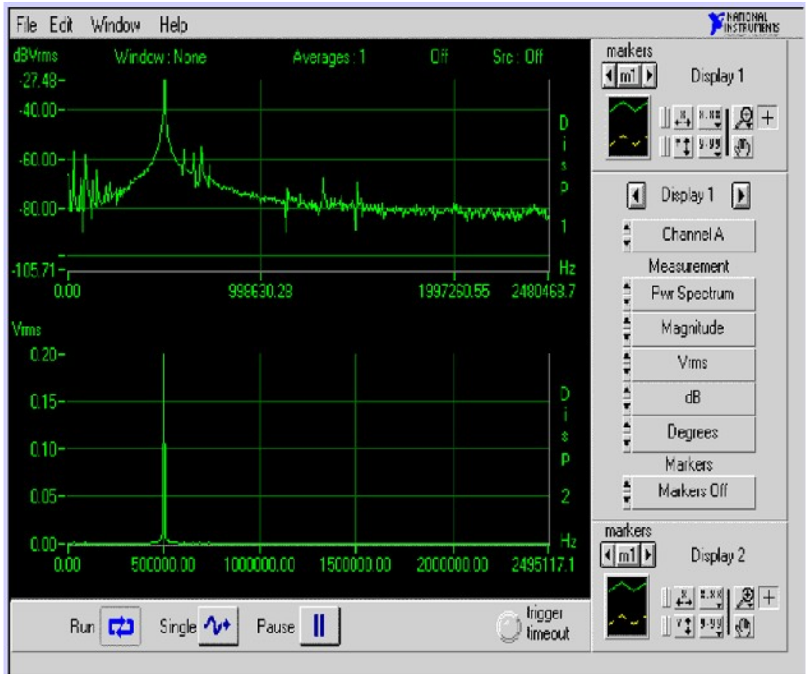


Figure 4: Resonance Characteristics in Earth Materials

Data Acquisition Approach

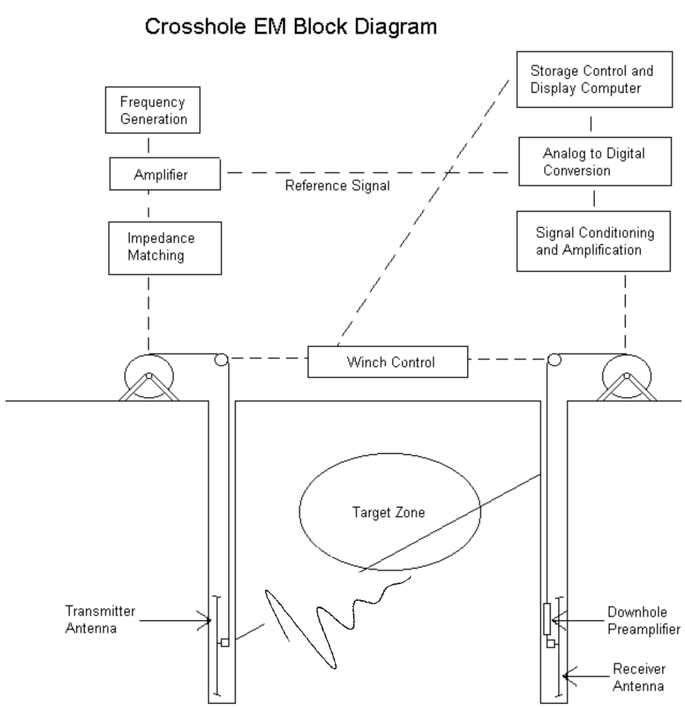
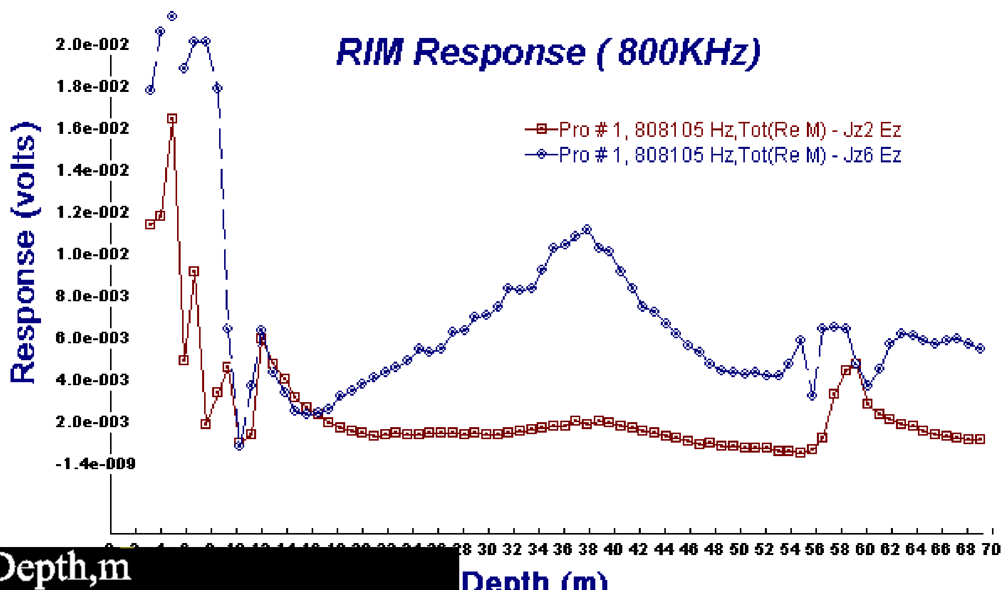


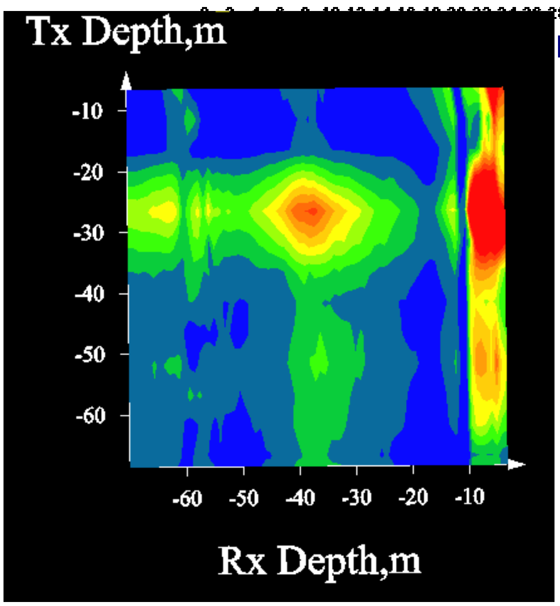
Figure 5: System components and standard survey setup.

Our initial approach was to use a National Instruments 6110 board installed in a standard desktop computer . The board is a 12 bit, 4 channel board sampling at 5 million samples per second. It has separate a/d circuits each with a programmable gain amplifier. We log an entire times series and then FFT the resulting time series to recover the received signal at the transmitted frequency. At present we are using surface electronics communicating with the antennae by coax cable. At first, we used no additional amplification except that provided by the a/d board and by the off-the-shelf signal generator but are now experimenting with additional amplification both at the transmitter and receiver ends to improve signal to noise levels when working in particularly noisy environments.

For a time series of length 4096, reading cycle time is about 5 seconds allowing readings of at as small as 30cm intervals although our standard measuring interval is approximately .9m.

Data Examples





The first example, is from 2 test holes located at the University of Waterloo in southern Ontario in an area of sand and silt. Both holes are 70m deep, vertical and separated by 15m. Figure 6 shows the received response when the transmitter is located at 5m (brown squares) and 37m (blue circles). The top 10m consists of find sand and silty sand with wet find sand at 10m , muddy medium grainded sand at 38m and a zone of coarse sand at 57m. The radiated frequency was 800Khz.

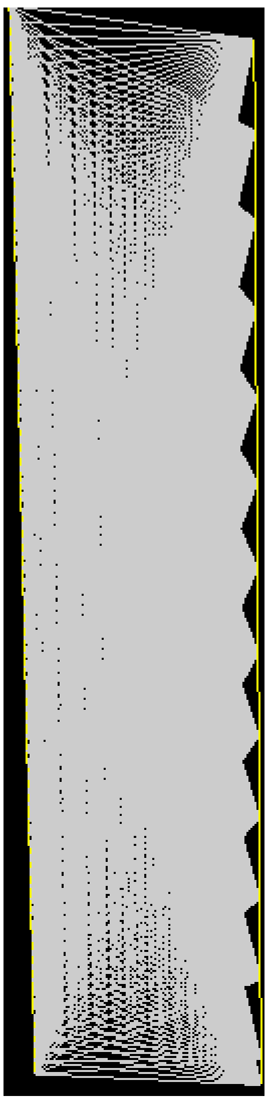
Figure 6: Data as a function of depth

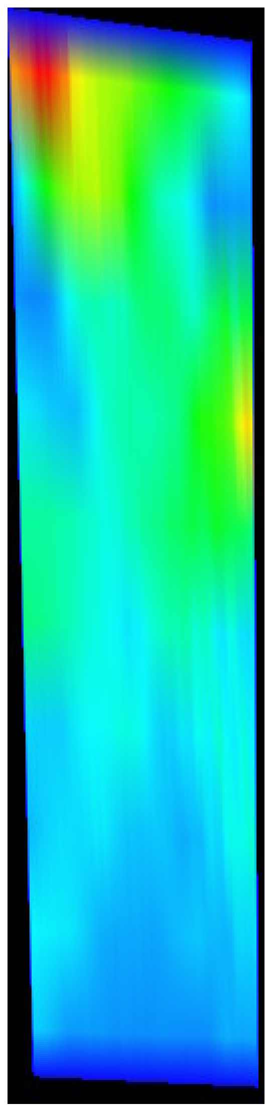
Figure 7 shows the data as a contour of amplitude as a function of transmitter depth versus receiver depth. Blue in the figure indicates low amplitudes increasing through green, yellow to red.

The data is collected by slowly hand cranking the winch with data collected automatically every .89m with the use of a magnetic trigger sensor. The transmitter was placed an increments of 5m down the other hole. From the logs and the soil and rock samples, it was expected to view a relatively layered environment. However, the data indicates a much more complex structure between the holes.

Figure 7: Data as a function of TX and RX depth.

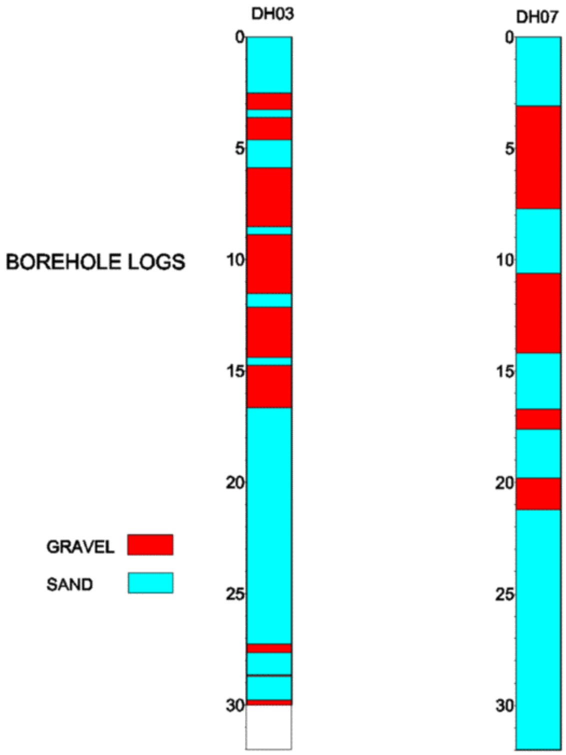
Another means of viewing the data is as a ray path tomogram. On the left (Figure 8a) we see the signal coverage approximated as ray paths. (The transmitter hole is on the right). In this figure, we draw lines between transmitter and receiver to indicate data coverage. The section between the holes is then divided into rectangular segments which is this case are 10 sections laterally and 50 sections vertically. The data is then analysed with each segment weighted by signal amplitude and proportioned according to ray's length in the segment (Figure 8b). In this case, blue is low amplitude and red high amplitude.





The data can then be processed by attenuation tomography (Figure 8c). In this case, three iterations were made of the attenuation tomography and the characteristics of the attenuation displayed. Blue indicates high attenuation, green moderate and red low.

Of course, attenuation is only one possible scattering possibility for electromagnetic wave at these frequencies and thus the displays have to be viewed as data images.



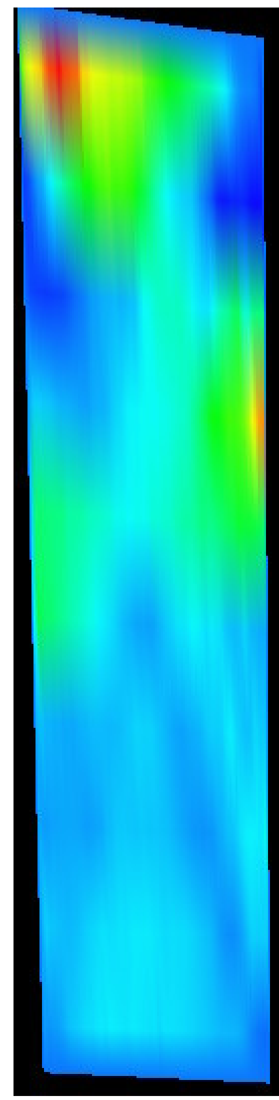


Figure 8a **Figure 8b** **Figure 8c**

Another test was performed in shallow monitoring holes within glacio-fluvial fill outside a large water reservior earthen dam in the Vancouver area. In this case, one reverse panel of data was collected. That is the data was first collected with the TX in one hole and the Rx in the other and then reversing the configuration.

Figure 9 indicates the depth of the two holes and the general variation of the glacial-fluvial till as a function of depth.

In this case, operating at relatively low frequency (500 KHz) enabled us to obtain greater sensitivity in this weak conductivity contrast environment. As well, the short antennae design (3m) enables the system's use in shallow applications (30 m holes). Whereas, other commercially available RIM antennae are 10 times longer for low frequencies and 2 times longer for high frequencies. In addition, the low frequency reduces attenuation allowing for larger hole separations. In this case, the holes are separated by some 40m.

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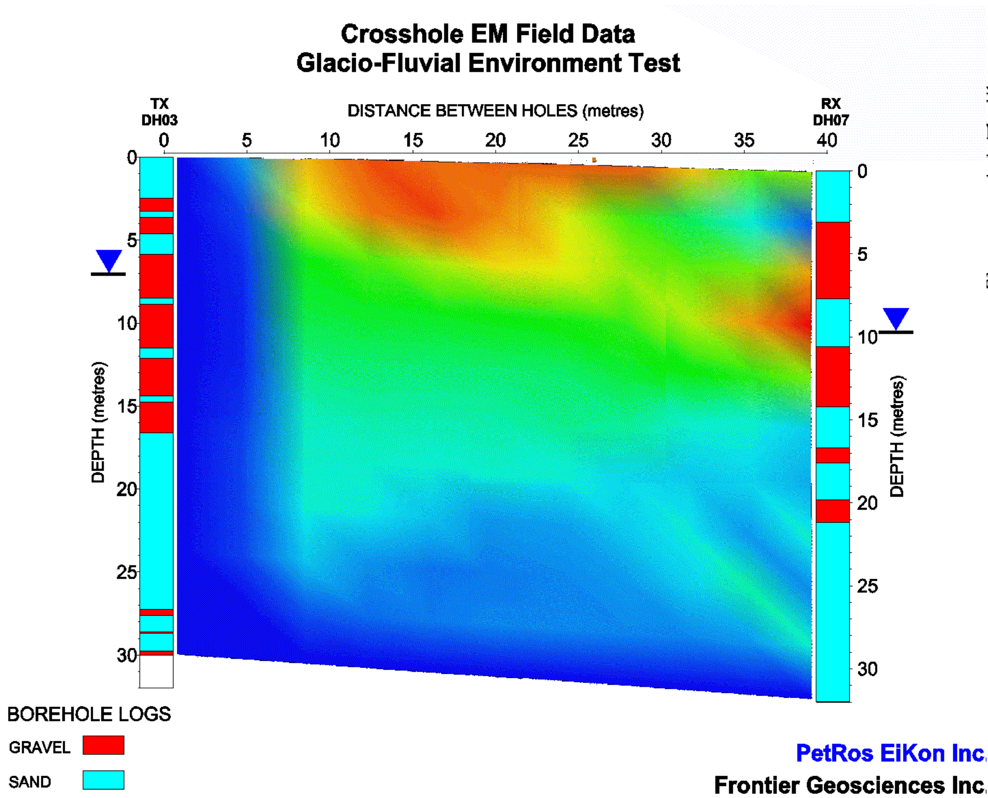


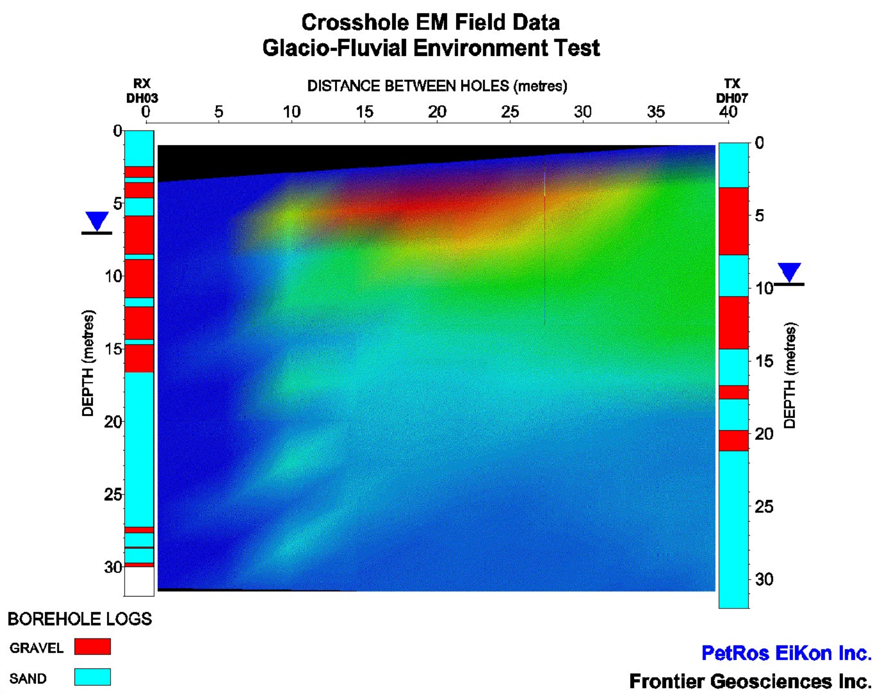
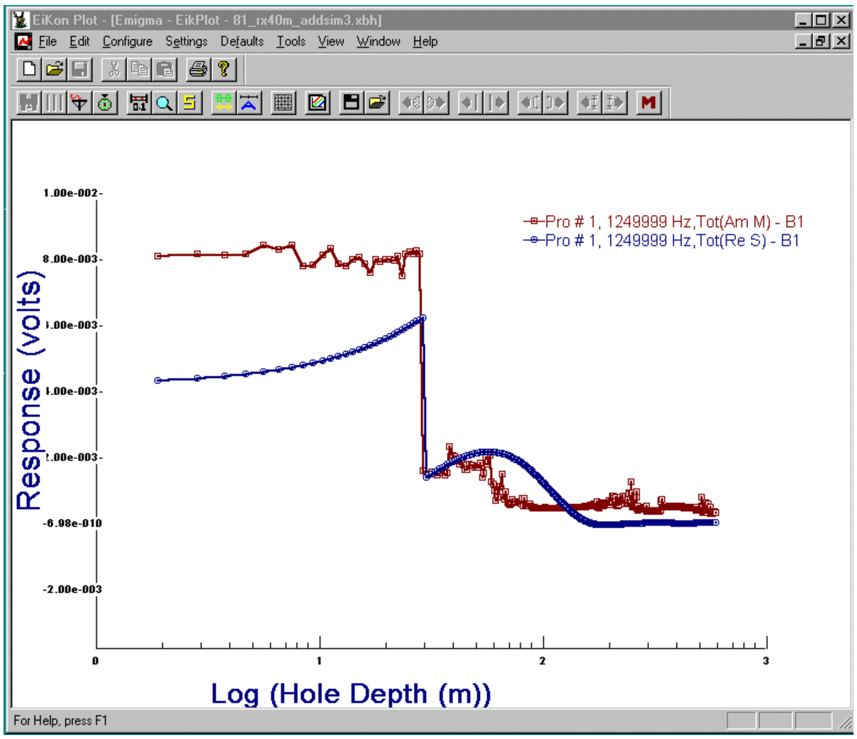


Figure 10b.

Radiation Patterns and Attennae Simulation:

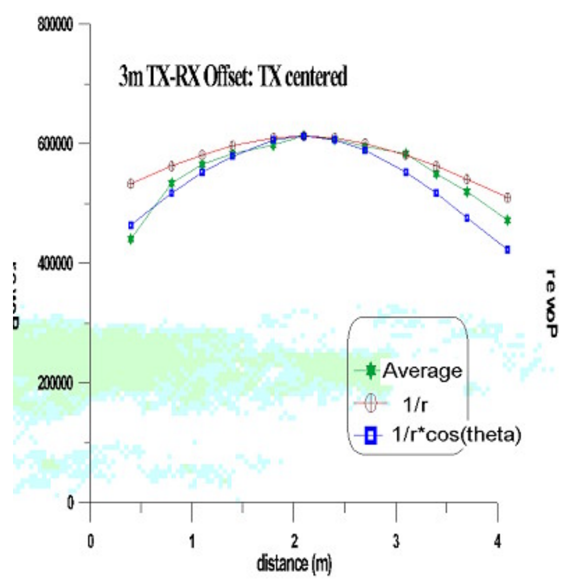
Figure 10Figure 10

Figure 7



As part of our research, we are attempting simulation of the antennae radiation patterns as well as the propagation of the waves through a complex medium. As part of this process, we first plotted the data amplitude as a function of distance in freespace and compared it to theoretical radiation patterns for a line attenna. In Figure 11, we see the data amplitude as a function of position versus theoretical 1/r and cos(θ)1/r functions. In this case, the TX and RX offset was 3m and the receiver was moved laterally to either side. This enable us to calibrate an amplitude for our attennae radiation power from which to compare measured and simulated data in a more complex environment.

Figure 11: Antennae Radiation Patterns



In this example, the 2 holes are located in a much more resistive environment in the Sudbury basin of Northern Ontario. The holes have been drilled for mining purposes and are located quite close to an operating mine. Although the holes are more than a kilometre deep, we logged the holes with our system only to a depth of 600m. The 2 holes are separated by a distance of 125m.

Our main purpose was to test our ability to simulate the signal. In this case, we knew from borehole resistivity logs that there was a strong interface boundary at 30m. The top rocks were indicated to be extremely resistive (20,000 Ohm-m)

Figure 11:

and the underlaying rocks somewhat more conducting (5,000 Ohm-m). For this test, the TX was placed at a depth of 50m and data collected in the other hole to 600m. Utilizing our understanding of the radiation pattern of the antennae and a Hankel transform technique we simulated the signal at the receiver. In Figure 11, we see the data (1.25MHz) plotted in brown as a function of depth and the simulation plotted in blue. Although we do not match the response exactly, we do simulate approximately the correct amplitudes, the sharp drop in amplitude at the lithological boundary, the rounding of the response at the depth of the TX and the general fall-off as a function of depth.

The ability to simulate the radiation characteristics of the antennae is extremely important as we eventually wish to perform 3D inversions on the data. Since, we do no anticipate either from general theory or from simulation that the scattering characteristics are simply antennuation, we must be able to simulate the full scattering response in three dimensions to provide more precise structural determination.