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**Enhancements to and Characterization of the Very Early Time
Electromagnetic (VETEM) Prototype Instrument and Applications to
Shallow Subsurface Imaging at Sites in the DOE Complex**

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TABLE OF CONTENTS

1.	COVER SHEET	1
2.	TABLE OF CONTENTS.....	2
3.	EXECUTIVE SUMMARY.....	3
4.	RESEARCH OBJECTIVES.....	4
5.	METHODS AND RESULTS.....	5
	5.1 Related Technologies and Methods	5
	5.2 VETEM Instrumentation	8
	5.3 VETEM System Operation and Data	21
	5.4 Data Processing and Visualization	25
	5.5 VETEM Numerical Modeling	29
	5.6 VETEM Tests and Deployments	45
	5.7 Assessing VETEM	55
6.	RELEVANCE, IMPACT, AND TECHNOLOGY TRANSFER	58
	a. Impact of results on DOE environmental management problems	58
	b. Benefit of results to improving cleanup technologies: cost, risk,	58
	and schedule	
	c. Extent to which results bridge the gap between research and	58
	application	
	d. Relevance of research to other laboratories	58
	e. Utility of findings to future technologies	59
	f. Impact on collaborators	59
	g. Advances in understanding	59
	h. Further work necessary to realize ultimate goal	59
	i. Interest in work expressed by other agencies and media	60
7.	PROJECT PRODUCTIVITY	60
8.	PERSONNEL SUPPORTED	60
9.	PUBLICATIONS	61
10.	INTERACTIONS	63
11.	TRANSITIONS	64
12.	PATENTS	64
13.	FUTURE WORK	64
14.	ACKNOWLEDGEMENTS	64
15.	DISCLAIMER	64
16.	LITERATURE CITED	65

3. EXECUTIVE SUMMARY

The central aim of the Very Early Time Electromagnetic (VETEM) EMSP project was to improve the state-of-the-art of electromagnetic imaging of the shallow (0 to about 5 m) subsurface through electrically conductive soils. In addition, we aimed to demonstrate the utility of the new technology by applications to sites in the Department of Energy (DOE) complex. We have approached needed improvements by developing new equipment and new numerical modeling to more fully exploit and interpret field data. We also were fortunate not only to have been given the opportunity to do test demonstrations of VETEM at a simulated waste pit, but to deploy VETEM at actual waste pits at the Idaho National Engineering and Environmental Laboratory (INEEL).

Instrument enhancements to VETEM include the development of new antennas and antenna geometries. Perpendicular, overlapped, and gradiometer loop configurations were developed as well as new electric field dipole antennas. New receivers, new transmitters, and a new platform were developed and new towing vehicles acquired. A Real-Time Kinematic Global Positioning system was integrated into the VETEM system for accurate spatial location of data.

The numerical modeling performed by the University of Illinois has advanced the state-of-the-art with respect to low-frequency modeling of antennas, and one, two, and three-dimensional forward modeling appropriate to the VETEM system. In addition, a 1D Distorted Born Approximation inverse model has been developed for VETEM that has been successfully applied to actual field data from Pit 9 at INEEL to estimate depths to buried waste.

Field tests and deployments of the VETEM system included the Cold Test Pit at INEEL, Pit 9 in the Radioactive Waste Management Complex (RWMC) at INEEL, Pits 4 and 10, also at the RWMC, and a former munitions foundry site at the Denver Federal Center. Our assessment of these results is that VETEM is a flexible and highly effective new system for electromagnetic imaging and, with the University of Illinois inversion algorithm, offers significant new 3D electromagnetic imaging capabilities in the shallow subsurface.

Products of this research include important new numerical modeling techniques, documented in numerous papers, applicable to electromagnetic subsurface imaging, and suggest further research and development. In addition, this research has also produced a flexible, fast, and fully functional prototype VETEM system that has produced some remarkable subsurface images, has bridged the gap between pure research and applications, and is now available for use at DOE sites that have shallow subsurface imaging needs.

4. RESEARCH OBJECTIVES

Nuclear weapons and energy related research, much of it conducted during wartime and other conditions of national stress, has left the DOE with a legacy of large quantities of radiometric, chemical, and other wastes. In some cases, past disposal practices for hazardous wastes have been inadequate to ensure the health and safety of DOE workers and the public. Environmental Management activities within the DOE aim broadly to assess and effectively deal with environmental problems resulting from past or current activities.

One need within Environmental Management activities is to develop improved methods for subsurface imaging, whether by seismic, electromagnetic, magnetic, radiometric, resistivity, or other techniques. Possible applications of electromagnetic subsurface imaging within the DOE complex include:

- waste pit and trench location,
- characterization of the contents of pits and trenches,
- assuring the thickness and conformance to construction standards of waste pit caps,
- periodic imaging of pit caps to assess longer term integrity,
- assessment of shallow grout injections,
- monitoring DNAPL and LNAPL spills and cleanup,
- characterizing the vadose zone by mapping geologic structures that have electrical conductivity contrasts that may be related to differences in hydraulic conductivity.

Specific research objectives of this EMSP project, 60162, are given below.

- Enhance the state of the art of shallow (0 to ~5 m) electromagnetic subsurface imaging in conductive earth.
- Achieve better penetration than GPR in conductive earth.
- Achieve better resolution than conventional time-domain EM systems in the first 5 meters of depth.
- Develop forward and inverse numerical models appropriate to the VETEM system, including at least a fast 1D inverse modeling code for in-the-field interpretation.
- Determine the effectiveness of the VETEM system by field applications at DOE sites.

5.0 METHODS AND RESULTS

In this section we discuss the specifics of both the instrument and numerical modeling research that was conducted.

5.1 Related Technologies and Methods

Even though this is a report on one technology for imaging the subsurface of the earth and objects buried in the subsurface, it may be worth putting VETEM into its context. We limit this discussion to electromagnetic (in the broad sense) techniques, and further narrow the scope to those methods that have some overlap in terms of spectral content to those used in VETEM. It is unfortunate, but true, that there is no single “one size fits all” geophysical instrument for subsurface imaging. The methods and instruments must fit the application and environment, and there is real merit to using several complementary geophysical techniques, for example seismic, magnetic, and electromagnetic in conjunction for a given application, selecting, of course, only those methods that are appropriate to the site and the application.

5.1.1 Ground-Penetrating Radar

Ground-penetrating radar (GPR) is a tool with many applications and, where it can achieve the desired depth of penetration, it is often the electromagnetic tool of choice because it can provide high resolution and the data can often be partially interpreted by inspection. In fact, when equipped with the electric field dipole antennas, the existing VETEM is a low frequency GPR. Unfortunately, when the electrical conductivity is high, as in typical clay caps over waste pits, GPR cannot penetrate far enough for many applications [1]. A recent comparison between VETEM loop antenna results and VETEM electric field dipole results is given in Wright and others [2]. An additional consideration is that it is usually assumed with GPR that propagation is essentially without dispersion (frequency dependent velocity). This assumption is not valid for high conductivities and low frequencies [2]. At the least, more sophisticated methods must be used for data visualization, inversion, and interpretation when dispersion is strong. A good beginning is a 1D forward model for GPR by Powers and Olhoeft that includes dispersion [3]. This model, however, makes far-field assumptions that are not valid for the majority of our data, even the electric field dipole data. Powers is considering modifying his model to allow near-field results to be calculated. If that is done we may have an additional tool for evaluation of VETEM data.

5.1.2 Electromagnetic Induction Systems

In order to achieve greater penetration in conductive earth, much lower frequencies are often used. There is a considerable array of such systems by Geonics, Geophex, Zonge, EMI/Geometrics, DUALEM, and others, and we will not attempt to review them all here. They generally operate at low enough frequencies that diffusion rather than wave propagation governs the induced earth currents and resulting fields. A variety of such instruments was used at INEEL as part of the Electromagnetics Integrated Demonstration

(EMID) and some discussion of those systems may be found in a paper on EMID [4]. The first VETEM prototype was also part of the EMID study [5]. A loss of resolution often accompanies the use of lower frequencies. VETEM typically operates in a portion of the electromagnetic spectrum intermediate between those used by typical GPR and typical EM induction systems. VETEM operation is fast and our results demonstrate that our use of an intermediate part of the frequency spectrum is providing high-resolution data that, in some field conditions, cannot be obtained with either GPR or conventional EM systems.

There are a few frequency domain systems that operate in the VETEM frequency range, including the High Frequency Sounder (HFS), designed and built by the USGS [6], and the University of Arizona LASI High Frequency Ellipticity System [7-9]. There are legitimate arguments that can be advanced for frequency domain measurements, but frequency-domain instruments have often been significantly slower, so we have concentrated on time-domain measurements for VETEM. The data cycle-time difference between time-domain and frequency-domain instruments depends on the particular instruments, but we wanted VETEM to be fast enough that we could obtain data while continuously profiling without stopping. We have achieved this goal with VETEM. Both the HFS and the LASI systems currently take data while the systems are stopped.

5.1.3 Electromagnetic Impedance Measurements

These methods are based on taking ratios of field components generated by a source usually in, or assumed to be in, the far field and deriving conductivity profiles in the earth from these measurements. Magnetotellurics (MT) and Audio Magnetotellurics (AMT) use natural sources. Controlled Source Audio Magnetotellurics (CSAMT) utilizes some controlled source as implied in the name. Recently, interest has increased in moving these deep-penetrating methods to higher frequencies to gain resolution for imaging the electromagnetic properties of the relatively shallow subsurface (for vadose zone studies, for example). The development of a high frequency electromagnetic impedance sensor, [10], and the more recent “High Frequency Electromagnetic Impedance Imaging for Vadose Zone and Groundwater Characterization” [11] are examples of projects funded by the EMSP that are working to extend impedance technology and practice.

5.1.4 Frequency-Domain and Time-Domain Instrumentation

It is well known that there is a mathematical equivalence between time and frequency domains through the Fourier Transform. It is therefore theoretically possible to develop equipment operating in the frequency domain that can perform functions equivalent to those of any time domain instrument. Indeed, many frequency domain instruments have been developed. Examples are “synthetic pulse” or “stepped frequency” GPRs. There are also a number of frequency domain electromagnetic induction systems, both commercial and prototype. Despite the theoretical equivalence between time and frequency domains, there are practical hardware differences. Arguments for frequency domain instruments include the ability to implement narrow-band filters to reject noise, and the ability to avoid frequencies where there is interference due to local radio stations,

for example. In addition, many forward and inverse numerical algorithms are written in the frequency domain, so no Fourier transformation of the data is required. However, the Fast Fourier Transform (FFT) is so fast on modern machines that the time required for a transformation from the time to the frequency domain is negligible.

A difficulty with frequency domain systems is that with a frequency domain system the receiver must often have a high dynamic range because the system must measure very small “secondary” signals from targets in the presence of the very large “primary” signal from the transmitter. One means of mitigation of this problem is to use some “null-coupled” antenna geometry, for example the use of a horizontal transmitter loop antenna with a vertical (perpendicular) receiver loop. Use of “bucking” signals is another option. With traditional time domain systems, the receiver is not turned on until some time after the transmitter is turned off, thus relaxing the requirement for high dynamic range in the receiver. In addition, frequency domain systems that operate at a large number of frequencies have been relatively slow because it takes time for the transmitter and receiver to switch and settle at each frequency. High-speed network analyzers can mitigate this disadvantage. Noise reduction with time domain systems can be accomplished using real-time waveform averaging, as implemented in VETEM.

Although we chose to implement a time domain system, VETEM, and we are pleased with our results, we think that the DOE community should not conclude that either time or frequency domain instruments are clearly superior in every respect or situation. It is beyond the scope of this report to attempt a definitive comparison between the classes of instruments. Each has its advantages and disadvantages, and improvements in technology in either domain could alter any conclusion we might offer.

The remainder of this report deals mainly with VETEM specifics.

5.2 VETEM Instrumentation

In this section of the report we discuss the VETEM instrumentation developed under the current EMSP research.

5.2.1 System Block Diagram

The system block diagram is shown in Figure 1.

Figure 1. The VETEM system block diagram including Global Positioning System.

Readers familiar with GPR will notice that functionally the block diagram looks very much like that of a time-domain GPR system. Significant differences between VETEM and most GPR systems include:

- VETEM can use either electric field antennas as a GPR, or loop antennas, as a TDEM system,
- VETEM uses real-time full waveform digitizing and averaging to improve signal-to-noise ratio,
- all data and command communications to and from the transmitter and receiver are via fiber optic links to avoid unwanted induced currents on wires, and
- Real-time kinematic global positioning system (GPS) data are part of the VETEM data stream.

Similarities to many GPR systems include the real-time data display that allows the user to immediately spot any system malfunctions and note areas that have significant features in them.

5.2.2 Full Waveform Digitizing and Real-Time Averaging

The VETEM system has a unique feature that has, so far as we know, never been implemented in any commercial GPR or TDEM system; namely, real-time averaging of digitized waveforms. In commercial time-domain GPR systems there is an analog sampling (or sample-and-hold) circuit in front of the digitizer. Every time the transmitter fires, the sampler takes just one sample of the radio frequency (RF) repetitive waveform. If it takes 1000 discrete samples to adequately represent the original continuous waveform, the transmitter must fire 1000 times before one full sampled and digitized replica of the RF waveform can be formed. With VETEM, on the other hand, a fast digitizer is used that digitizes all the points in each and every waveform.

In order to achieve improved signal-to-noise levels, almost all time-domain GPRs use coherent waveform addition. For random uncorrelated noise with white Gaussian statistics, the improvement in signal-to-noise level, in decibels, is $10\log_{10}N$, where N is the number of waveforms averaged. If every waveform is digitized and averaged, the signal-to-noise ratio may be improved 100 to 1000 times faster than with a repetitive single-point sampling method.

Fast digitizers, similar to the one in VETEM, have been available for some time and are the basis for many fast digital oscilloscopes. What those oscilloscopes lack, however, is the ability to summation average the waveforms at a fast enough rate to keep up with the VETEM repetition rate which is variable, but typically 10 kHz.

The USGS has been a pioneer in real-time averaging and built several units that could average in real time. The first of these was built and fielded in 1987 [12],[13]. One of the USGS units was, in fact, used in recording data from the first, pre-EMSP, VETEM prototype. That unit had more analog bandwidth than required, 1000 MHz, and served us well. However, it had several disadvantages for VETEM use. It was heavy, bulky, generated lots of heat, and was a power hog. In the current EMSP research we found, and incorporated into VETEM, a set of commercial computer boards that will replicate most of the functions of the USGS digitizer/averager and has several practical advantages. The boards are much lighter, consume much less power, generate little heat, and plug into two ISA slots in a computer, thus requiring no additional bulk. The unit is a customized Precision Instruments, Incorporated, Model 9826 [14]. The customization we requested was to modify the unit to permit it to be run from an external 500 MHz clock, as well as its own internal 500 MHz clock. The reason we requested this modification is that we need to be able to synchronize our transmitter triggers to the clock to ensure close time synchronization for phase coherence in our signal averaging. This is especially important for fast waveforms that result, for example, when electric field antennas are used. The 9826 digitizer/averager can digitize at a 2 ns digitizing interval and can easily average 8192 points (our most frequently used record length) at a 10kHz, or higher, repetition rate. As an aside, it is our understanding that the Model 9826 was developed for high energy physics applications at the Oak Ridge National Laboratory (ORNL). Our application is an unusual one for the 9826, but it meets VETEM needs,

and we were happy to find an additional use for a product designed to meet another DOE need.

5.2.3 Transmitters

There are now three VETEM transmitters from which to choose. Each is appropriate for different applications and antennas.

- A preexisting programmable pulse length, constant current, fast turn-off, transmitter that can sustain a current of 1 A for about 1 μ s when driving a 10.5-inch diameter loop antenna.
- A programmable length ramp current transmitter that can attain a peak current of as much as 30 Amperes into our 30-inch square loop antennas. The current ramps up at approximately 6 A/ μ s, and turns off at approximately 60 A/ μ s when driving the 30-inch square loops.
- An avalanche transistor pulser designed for use with electric field dipole or the 10.5-inch diameter loops.

An unusual feature of all of the transmitters is that each is equipped with a current sensor so that the actual current output pulse can be recorded. This capability might be needed in the event that the transmitter current varied significantly as the antenna was moved over areas of varying conductivities. For the 30-inch square loop antennas, measurements have indicated relatively little loading, so it appears in most cases that a static measured current is sufficiently accurate as input to the inversion algorithm.

5.2.4 Receivers

The VETEM system also has three receivers. All are equipped with a programmable attenuator so that the overall gain can be set appropriately for the signal conditions.

- A preexisting linear receiver with a bandwidth from about 6 kHz to 70 MHz. This receiver was designed to allow the choice between measurement of the current through a shorted receiver loop (proportional to the magnetic field), or the voltage at the loop driving point when the loop is effectively open circuited (proportional to the time derivative of the magnetic field). The choice can be selected remotely by the operator. Inclusion of the option was done at an early date because some modelers seemed to prefer one or the other measurement. In practice, however, we now generally measure the current. The main reason for this choice is that the dynamic range of the received signal is smaller, which reduces the dynamic range requirement in the receiver. When measuring the current the low frequency roll-off, or decay time, is set by the Tektronix CT-1 current transformer used to sense the receiver loop current [15]. Our measurements indicate that the CT-1 in this application has better low frequency characteristics than guaranteed by Tektronix.
- A linear receiver with a bandwidth of 20 kHz to 200 MHz was designed for use with the electric field dipole antennas and has been used exclusively in that role.
- A linear/logarithmic receiver was designed to improve the dynamic range of the receiver. This receiver preserves the option of measuring current or voltage at the receiving loop. It is also equipped with programmable low-pass hardware filters with

a high frequency 3 dB point of 400 kHz, 50 MHz, or 200 MHz. The unusual linear/logarithmic nature of this receiver permits expanded dynamic range for the received signal. Another feature of this receiver is the ability, under software control, to switch between two orthogonal receiving antennas in the event that both perpendicular and co-planar measurements are desired. This new receiver was completed in time for the survey of Pits 4 and 10 at INEEL. Pit 9 was surveyed using the original linear receiver.

5.2.6 Spectral Content

Of the three transmitters, the ramp-current model has been the most used to date. Figure 2 shows a typical waveform and the related amplitude spectrum for this transmitter. The waveform can be shortened to push the spectral content up for higher shallow resolution, or it can be lengthened to achieve higher peak current with lower spectral content. Lower spectral content and higher peak currents are better suited for deeper penetration. Figure 3 shows a typical received waveform and the higher spectral content when using the avalanche transistor pulser with the electric field dipole antennas.

Figure 2. An example VETEM waveform (top) and amplitude spectrum (bottom).

Figure 3. An example waveform using an electric field dipole antenna (top) and corresponding amplitude spectrum (bottom). The top waveform is 1000 ns long.

Figure 4 shows where VETEM's spectral energy content is located in the electromagnetic spectrum. VETEM can overlap some EM induction systems and the lower part of GPR use. However, to achieve the full spectrum of which VETEM is currently capable, more than one antenna type must be used.

Figure 4. The part of the frequency spectrum utilized by VETEM overlaps some GPR and some EM induction systems.

5.2.7 Antennas

VETEM has been designed to allow considerable flexibility in the selection of antennas. The reason for such flexibility is that a wide variety of earth electrical properties may be encountered in practice, and we wanted VETEM to work under as wide a range of conditions as possible. The remainder of this section discusses several antennas and configurations of antennas that have been developed during this research. When we first began our VETEM research we anticipated that we would gate the receiver off while the transmitter is on, and turn it on at some very early time after transmitter turn-off. Time domain systems generally do gate the receiver off while the transmitter is active to reduce the dynamic range demanded of the receiving electronics. We found, however, that the data recorded during the ramp-up of the transmitter loop current responded very strongly to shallow subsurface conditions and objects. Therefore we decided to record data through the entire transmitter pulse and for some time after the transmitter has been turned off. This practice, of course, puts much greater demands on the receiver. To mitigate these demands, we have generally operated with some form of “null-coupled” antenna configuration. In a null-coupled configuration the “primary” field, i.e. the field that would exist in the absence of the earth, is ideally not sensed at all because of the geometrical relationship of the transmitting and receiving loops. We have experimented with four null-coupled geometries: spaced perpendicular loops, overlapped loops, and horizontal and vertical gradiometer loops.

5.2.7.1 Spaced Loop Antennas

Loop antennas have been the most commonly used types of antennas for VETEM because most of the situations encountered have been ones where the electrical conductivity of the earth has been somewhat too high for the higher frequencies used with GPR. At the INEEL Cold Test Pit, for example, GPR was tried as part of the Electromagnetic Integrated Demonstration (EMID) [4]. The GPR results were not considered to be very successful at the CTP. We have more to say on the subject of GPR in high conductivity soils in section 5.6.4 and in a paper [2].

The original preexisting VETEM prototype antennas were 10.5-inch diameter single turn circular loops. These antennas have a loop inductance of about 0.5 μH and do not become self-resonant until about 60 MHz. These loops were used in the EMID in 1995, prior to this research, and produced very encouraging results. However, we concluded that efforts to increase the depth of investigation were needed.

Under the present EMSP research larger loop antennas were fabricated. The first versions were 30-inch square loops on plywood frames. The area of these antennas is 10 times that of the original loops. These antennas were used for the Pit 9 survey at INEEL. Since that time these antennas have been replaced by loops of identical size, but built on much more rigid fiberglass frames. The antennas are single turn, and the conductor is a flat copper strip, to keep inductance low. The inductance of these loops is approximately 3 μH and the resistance is less than 0.1 ohm. Experimental results indicate that the

inductance generally dominates the impedance of the antennas for the conditions under which we are using them. These antennas are shown in Figure 5.

Figure 5. A common VETEM antenna configuration with a horizontal transmitting loop and both vertical and horizontal receiving loops. Also seen is a GPS antenna on the forward (left) end of the cart. The VETEM antenna spacing here is 2 m and the cart is over a metal calibration plate.

Other factors in the choice and use of antennas include the geometrical relationship of the antennas to each other, and the spacing between them. We have experimented with a number of configurations. Based mainly on observations of experimental data, we have come to rely primarily on a few configurations. The most commonly used of these is 2-m spaced perpendicular loops with the transmitting loop horizontal (generating a vertical magnetic field) and the receiving loop vertical (sensing the horizontal component of the magnetic field). This description of the antennas and fields is in terms of near-field quasi-static conditions. For much of our VETEM data these assumptions are valid. However, the University of Illinois numerical modeling of our antennas is not restricted to these conditions. As can be seen in Figure 5, the receiving antenna actually consists of two orthogonal loops, one vertical, and one horizontal. The receiver can be switched between these two so that both the horizontal and vertical fields can be recorded if desired. In practice, the co-planar configuration produces such a strong primary field that we generally have not used it, except at a 4-m antenna spacing, which we rarely use.

Some of our early experiments at the Cold Test Pit at INEEL included varying the co-planar and perpendicular loop antenna spacing. We have tried 1-m, 2-m, and 4-m spacings. At least for the conditions that exist at the CTP, it appeared that a 2-m spacing

was the best compromise between resolution and depth of investigation when using spaced antennas. The data did not clearly demonstrate improved depth of investigation using a 4-m spacing, but the horizontal resolution was significantly degraded. It does appear that we were getting better depth of investigation with 2-m spacing as opposed to 1-m spacing with acceptable loss in horizontal resolution. We settled on a 2-m spaced perpendicular configuration for our loops for Pits 9, 4, and 10. That is the configuration that the University of Illinois inversion code is currently set up to run. Parameter changes could be made to the code to handle other configurations, such as the vertical gradiometer, for which forward modeling has already been done, as discussed below in section 5.5.2.3.

5.2.7.2 Overlapped Loop Configuration

Another antenna configuration that proved quite favorable was overlapped loop antennas as shown in Figure 6. In this configuration, the antenna overlap is experimentally adjusted to minimize the receiver signal when the transmitter is on. The minimization adjustment allows an increase in the receiver gain so that the system is more sensitive to small secondary and scattered signals due to changes in earth electrical parameters or buried conducting objects.

Figure 6. Another useful VETEM antenna configuration is overlapped loops. The receiver (RX) and transmitter (TX) are also shown. The overlap of the antennas is adjusted to minimize primary field coupling between the TX antenna and the RX antenna.

We show a comparison of data taken at the Large Object Pit part of the CTP using perpendicular antennas and overlapped antennas in Figure 7. A general conclusion is that the two configurations yield similar results for objects of significant size at depth. However, the overlapped antennas are clearly more sensitive to small, discrete, near-surface, objects. This sensitivity is an advantage in some circumstances, but could become a disadvantage, for example, at a buried waste pit like Pit 9 at INEEL where all targets of interest are beneath a several foot thick clay cap, but some building construction debris had been left on the pit. We discuss the Pit 9 survey below.

Figure 7. Time-slice amplitude data from the INEEL Cold Test Pit using perpendicular (A.) and overlapped (B.) antennas. Higher amplitudes in this figure imply higher electrical conductivity and are mapped to hotter colors. Note the two doublets along line -45N, at about -8E and 50E in the bottom, but not the top panel. These are responses from relatively small, shallow pieces of metal.

With overlapped loops positional accuracy is critical to getting the lowest possible coupling between the transmitting loop and the receiving loop. Relative changes in position of as little as 1 mm between the antennas is significant. We experienced some mechanical shifts due to shock and vibration or thermal expansion/contraction overnight that introduced baseline shifts in our data. We think mm accuracy and stability is quite possible mechanically, but we did not fully pursue it because of a modeling limitation.

Most of our loop antenna configurations can be modeled by the University of Illinois codes, but the overlapped configuration is an exception. The very close proximity of the two loops makes modeling their interaction difficult. Therefore we reduced the priority of the overlapped antennas, even though that configuration produced some of the best images we have seen from VETEM data.

5.2.7.3 Loop Gradiometer Configurations

We performed only one quick experiment using a co-planar horizontal loop gradiometer configuration, but the data were flawed because of equipment problems. This configuration still seems to us to have good potential, but we moved to a vertical gradiometer configuration because we wanted to obtain the highest possible horizontal resolution and we thought this configuration might yield horizontal resolutions similar to those obtained with overlapped loops. The central advantage would be that the vertical gradiometer configuration could be modeled and inverted using the University of Illinois 1D DBIM code.

A vertical gradiometer configuration (Figure 8) was the last to be developed and has been used only at the CTP at INEEL. The data show high horizontal resolution, but this configuration proved quite sensitive to height above the ground over the frequency spectrum we are using. In addition, the vertical gradiometer exhibited a great deal of “ringing” after transmitter turn-off over the CTP. This had not been observed during the gradiometer setup in Denver over the former munitions foundry site. We speculate that the higher conductivity at the Denver site, measured to be from about 67 mS/m to about 333 mS/m, damped the ringing. We regard the vertical gradiometer loop configuration as quite promising for VETEM, but in need of further development.

5.2.7.4 Electric Field Dipoles

For cases where the earth conductivity is not too high, VETEM can be configured to operate as a relatively low frequency GPR using the electric field dipole antennas shown in Figure 9. These antennas have a copper back-shield to reduce upward radiation. In addition, they are resistively loaded to damp ringing, and the space between the flat bow-tie dipole antenna and the back shield is filled with electromagnetically absorbing material to reduce cavity-resonance type ringing. Our experience with these antennas is very limited and was conducted at the Denver Federal Center over very conductive earth, 67 mS/m to about 333 mS/m, that is very unfavorable for GPR. The system did respond to buried structures and we would like to pursue further studies with and adjustments to these antennas, but simple time-slice displays of the raw data were not so clear as those

Figure 8. The vertical gradiometer configuration over the calibration ground plane.

produced with the loops [2]. No further work has been done using the electric field antennas, though we think they might perform quite well over less conductive soil.

Figure 9. The electric field dipole antennas are back-shielded and have internal RF absorbing material to minimize undesirable radiation into the air.

5.2.8 Cart

The pre-EMSP VETEM cart is shown in Figure 10. This cart permitted a maximum of 2-m separation between antennas using the 10.5-inch diameter loops. We discovered that the 4-wheel suspension put twisting forces on the cart bed when operated over uneven ground. We designed our new cart, Figure 9, to allow up to 4-m spacing between the larger loops. In addition, the new cart has a three-point suspension designed to eliminate twisting moments on the cart. Further, the new cart is fabricated from large cross-section fiberglass I-beams, and vertical posts and a top cross member have created a much stiffer structure without exacting a large weight penalty. The cart without antennas weighs about 220 pounds. Another important feature of the cart is that it is made almost entirely of non-metallic materials to avoid the possibility of inducing currents on the cart that would interfere with the measurements of fields from currents in the earth or objects buried in the earth. The height of the cart above ground is adjustable so that additional clearance is available over uneven ground and small obstacles. Compare Figures 8 and 9, for example.

Figure 10. The original VETEM cart with 4-wheel suspension carrying the smaller 10.5-inch diameter loop antennas at the Cold Test Pit, INEEL, 1995.

5.2.9 Towing Vehicles

When this research began, the VETEM cart was pulled by a winch in a borehole logging truck (Figures 11 and 12). This procedure has advantages and disadvantages. The winch can produce uniform speed and data density and accurate relative positioning along a line using the cable position encoder. Disadvantages include a requirement for one additional field person, much greater physical demands on the cart operators, no measurement of deviations from a line, no automatic absolute positioning, and speed penalties because the cart cannot be rapidly backed up. The winch towing method was the only one available when Pit 9 was surveyed. Pits 4 and 10 covered a much larger area, and it would have

Figure 11. View from inside (left) and outside (right) the borehole radar truck. The borehole radar winch, equipped with Kevlar-strengthened fiber-optic logging cable, was our initial means of towing the VETEM cart. This truck also tows the VETEM trailer for transportation of the VETEM system to work sites.

been impractical to use the truck winch for that survey. The VETEM system was converted so that it could be towed by an All-Terrain Vehicle (ATV). The ATV was used to survey Pits 4 and 10 at INEEL (Figure 12). As part of the conversion we added Real-Time Kinematic Global Positioning System (RTK-GPS) data to the data stream. Although the ATV was a huge improvement, ATVs are not designed to operate at a walking speed and we found it difficult on the operator and the centrifugal clutch of the ATV to operate at the walking speeds desirable for VETEM. In addition, our particular ATV was air-cooled and consistently overheated on hot days when operated at low speeds. The ATV has since been replaced by a small tractor, with a liquid-cooled engine, designed to operate at slow, steady, easily controlled speeds (Figure 13).

Figure 12. ATV-towed VETEM at INEEL.

Figure 13. Tractor-towed VETEM.

The tow bar is 3 meters long. The tow bar length was determined experimentally by backing an ATV slowly closer to the VETEM system while it was operating and watching the data to see when the effect of the ATV was just noticeable in the data, then

making the tow bar a little longer than this length. The small remaining interaction with the ATV is nearly constant, except in a sharp turn, so the effect should be quite negligible on residual (average response subtracted) data.

5.3 VETEM System Operation and Data

5.3.1 System Calibration

In order to invert field data using the University of Illinois code, it is necessary to remove the system response from the field data. The most effective way to do this is to calibrate the system over a nearly perfectly conducting ground plane with the same antennas, geometry, and antenna height that are used when recording field data. Figures 5 and 8 show the VETEM system being calibrated over a ground-plane at INEEL. The ground plane is 1/16" thick 4' by 8' aluminum sheets joined with copper tape with conductive adhesive. Daily or twice daily calibrations also serve to measure system stability. The system is now generally quite stable when care is taken to ensure that fiber-optic connectors are dust-free.

5.3.2 System Positioning

Our 1997 EMSP proposal focused on improvements, characterization and modeling, and applications of the VETEM system and took positioning largely for granted. However, discussions with INEEL regarding our first genuine deployment at Pit 9 made it clear that, in order for our geophysical data to be useful for the intended application, the data had to be spatially accurate. For the Pit 9 survey a grid was laid out with conventional surveying methods. The grid was referenced to known points with GPS. A series of parallel lines was run on the grid, and positions along each line were derived using the cable position optical shaft encoder. The methods we used were adequate for that survey.

However, when we were asked to survey Pits 4 and 10 at INEEL, it was apparent that the much larger areas involved would require changes to our field procedures. Specifically, the method of pulling the VETEM cart with a cable was going to be too slow because of the necessary repositioning of the horizontal sheave wheel and/or the truck after each line. We therefore modified our equipment so that it could be operated independently of the truck and pulled behind an ATV. This change required us to move to a Real-Time Kinematic Global Positioning System to get accurate positions referenced to some universally accepted coordinate system and recorded automatically as part of the VETEM data stream. We therefore integrated an Ashtek GG-12E RTK-GPS into the VETEM system. RTK-GPS provides consistent and known positioning. We have also written software to handle the inherent latency issues in the VETEM data and the GPS data. With respect to GPS this means that the GPS unit is putting out very accurate positions, but the position data is not where the roving antenna *is* instantaneously, but rather where it *was* when that position was acquired a short time ago. We use a fast GPS unit (1-second update rate) to reduce latency issues, but still compensate for the small remaining lag with our software. Since the Pits 4 and 10 surveys the USGS has purchased a more advanced Javad Legacy E RTK-GPS system that has dual frequency, GPS+GLONASS

(GLONASS is the Russian counterpart to the US GPS system). Our practical observations so far are that the positions are more accurate, but more important, the new unit acquires satellites faster and “dropouts” due to too few satellites and/or multi-path problems have not been observed. We did experience some dropouts with the single-frequency GPS unit.

5.3.4 Data Acquisition, Recording, and Archiving

Data acquisition procedures for VETEM are functionally similar to those that might be encountered with a commercial GPR unit. We wrote our data acquisition software mostly in “C” with a few C++ features added. Figure 14 shows an example of information that the operator enters before data acquisition is initiated. The information includes entries for site and line information, setup and control of the Precision Instruments A/D boards, real-time plotting, data file name and location, transmitter setup, and four receiver setup modules. The four receiver setup modules permit the system to automatically set the receiver to as many as four different states per acquisition cycle.

Figure 14. This figure illustrates the input information used to set up the VETEM data acquisition program.

The receiver can be set to alternate between vertical and horizontal loops, different attenuation (gain) states, and bandwidths, if desired. For example, in our work at Pit 4 and 10 at INEEL, we found it useful to cycle the receiver between two gain settings. In the higher setting the received waveform would go non-linear, and sometimes over large conductive targets the signal would even clip. The lower gain setting usually kept the received signal linear, or nearly linear, and prevented any clipping. In cases where clipping occurs at high gains, it is necessary to numerically reconstruct the clipped portions of the high gain data using the low gain, unclipped waveform. Figure 15 shows the graphical user interface (GUI) that is used to enter the data described above. Most of the information becomes part of an ASCII header string that is prefixed to each data record.

Figure 15. This Graphical User Interface (GUI) is used to enter the information necessary to operate the VETEM data acquisition software.

When the system is acquiring data, the data screen looks similar to that shown in Figure 16. The operator can verify at a glance that the system is operating properly and can also immediately determine when the system is over an area where the electromagnetic properties are different; over a large buried metal object, for example.

One element not mentioned in the data acquisition flow chart of Figure 14 is position information. Position information is supplied by the RTK-GPS. Once in each data

Figure 16. This real-time data display shows both individual waveforms (bottom) and a pseudo-color image of sequential traces similar to many GPR displays.

acquisition cycle the software downloads position information from the RTK-GPS over a serial (RS-232) computer port. This information becomes part of the header information that is prefixed to each data record. Date and time are also included in the header. There is enough space in the header to include comments about the data, conditions, or any other short comments. We have designed the data acquisition to be as nearly stand-alone as possible though, as a matter of good field practice, we also maintain a hand-written field notebook with entries keyed to the file naming convention.

In order to avoid dust, shock, and vibration problems with mechanical media, all data are written to a RAM drive during acquisition. Thus no moving parts are required in the computer system while VETEM is moving. Data are stored on a SanDisk Flash Drive model # SD35B-192. This unit is solid state memory with robust environmental specifications including an operating temperature range of 0° to 60°C, operating vibration level of 15 G peak to peak, and an operating shock rating of 1000 G maximum. Data are written to this drive during data collection.

When the RAM disk is nearly full the software flags the user of the condition and we stop the VETEM system and download the data from the RAM disk to an external JAZ drive equipped with a SCSI interface. In addition, as soon as possible, the data are also archived on CDs using a write-once CD writer.

5.4 Data Processing and Visualization

In order to prepare the data so that maps may be produced and the data converted to a form that is ready for the University of Illinois DBIM algorithm, some processing is necessary. Our processing software is written in IDL (Interactive Data Language) [16]. We chose IDL because it is designed for scientific data processing and visualization and includes a large number of direct and object oriented graphics functions. We choose to run IDL on Windows 95, 98, NT, and 2000 operating systems, although versions of IDL for UNIX, LINUX, and some other operating systems are also available.

5.4.1 Preprocessor

Before images can be generated, the data must pass through several steps. Some are sequential and mandatory, others are optional for enhanced perspectives on the data and for flexible output formats. The final output of the preprocessor is a structured data file used by the main VETEM image processing application [17].

5.4.1.1 Data Validation

Receiver data validation checks each record for spurious measurements. The digitizer occasionally exhibits offset errors, or “glitches”, in the sample window of 425 to 455, which corresponds to times when the transmitter is on and ramping up. Although these are unlikely to affect subsequent processing steps, they are discarded and replaced with interpolated values. Position values are checked for acceptable differential changes. An occasional error in the RS-232 data transmission causes an anomalous position reading. Erroneous positions are removed.

5.4.1.2 Assign Coordinates

The preprocessor reads the RTK-GPS position information from the header of each record. Typically, the latitude and longitude coordinates are then converted into universal transverse Mercator (UTM) coordinates using the computer program Corpscon [18]. The data are also corrected for the offset from the GPS antenna to the center of the VETEM antenna array, and for data latency.

5.4.1.3 Calculate Residual

Once the data are validated, the raw data profile is displayed (Figure 17). Residual images display deviations from a static background. Residual data are obtained by subtracting an average waveform from each raw data record in a line. Statistics are computed for all the waveforms along a line, and a criterion of 1.6σ , where σ is the standard deviation, is used to include waveforms in the averaging. Waveforms that exceed 1.6σ are omitted from the total. The residual profile is displayed in the main graphics window with hatchures on those data records excluded from the averaging process (Figure 18).

Figure 17. View of raw profile data.

Figure 18. View of residual profile data.

5.4.1.4 Write to ASV file

The most efficient method of input/output in IDL uses an associated variable (ASV) file, in which data records are stored as a structure-type variable. VETEM associated variable file records are written as {X, Y, FID, waveform}, where X, Y are the x- and y-coordinates, FID stands for file ID, and waveform consists of n-sample unsigned integers, where n-sample is the number of samples per waveform, usually 8192. For a given survey line, the raw data records are output first, followed by the waveform average for that line. Since development of the linear/logarithmic receiver, a new file type, ASF, has been defined to accommodate the floating-point data representation needed to handle the increased dynamic range and linearization of nonlinear data recorded when using that receiver.

5.4.1.5 Optional selections

A “Variogram” menu selection offers several ways to view variograms of the data (Figure 19). Variograms are useful in characterizing the baseline noise over the waveform, and in identifying sections of the waveform most suitable for the σ -cutoff criterion used to calculate the waveform average.

A “Waveform Processor” utility allows access to each waveform in the line. Options include smoothing, derivatives, spline fitting, and fast Fourier transform (FFT). Moving the cursor over the main graphics window displays record number, and clicking the cursor activates a menu to save the selected waveform to an ASCII file.

5.4.2 Postprocessor

The VETEM application comprises numerous postprocessor functions, accessible through pull-down menus at the top of the GUI, which presents the user with three window panes (Figure 20). The largest, left pane displays the two-dimensional image

Figure 19. A variogram display.

Figure 20. An application screen.

along with readouts of coordinates, data values, and graphical annotations. The middle pane provides an interactive view of a waveform for picking times for time slices. The right pane displays profiles along transects defined by cursor in the left pane. Data input to the postprocessor is a structured data file prepared by the VETEM preprocessor. The preprocessor can be invoked from within the VETEM application. “File” services offered include loading and saving data in a variety of formats, including native ASV, ASCII, PostScript, and JPG. Color scales for pseudocolor images are determined by the “Colors” selection, by which the user can activate a color-table routine that permits exquisite control of image color values (Figure 21). One option provides for histogram equalization of an image. The HISTOGRAM function is used to obtain the density distribution of the input array. The histogram is integrated to obtain the cumulative density-probability function and finally the lookup function is used to transform to the output image. The data are manipulated for graphical display by a “Data Processing” pull-down menu. It offers a variety of gridding and interpolation routines (inverse squared, Delaunay triangulation, raw fill), 2D matrix smoothing to different widths, access to raw and residual data, scaling of data values logarithmically according to user input. The “Contours” menu facilitates the plotting of contours (Figure 22).

Figure 21. Color control screen.

Figure 22. Example of Contoured Data.

The “Image” menu supplies the user with routines to mask and unmask areas of the image using resizable cursor-controlled boxes. For example, a region with strong amplitude signals can be masked in order to accentuate weaker amplitude anomalies.

A “Profiles” menu provides a method to display data profiles along a line superimposed on the image with the cursor. The user can specify the number of profiles and the time increment. The profiles appear in the right pane, with the selected times indicated in the middle waveform pane.

5.4.2.1 Persistence

The “Persistence” selection under “Data Processing” applies an algorithm based on the persistence of the early-time induced currents in extensive subsurface conductors. The time constant, τ , is defined as the time it takes for the received signal to fall to $1/e$ of a former value, where “e” is the base of natural logarithms (2.71828...). That is: $\tau = t_1 - t_0$, for $A(t_1) = A(t_0)/e$, where A is signal amplitude, t_0 is an earlier (reference) time, and t_1 is a later time. This early-time decay depends primarily on the geometric extent of underground conductors. Late-time decay, as measured by traditional time-domain EM techniques, depends on the conductivity value of the body [19]. The resulting plot delineates areas of differing signal persistence. Contours of persistence overlaid on a pseudocolor time slice image in Figure 23 mainly circumscribe the strong conductivity anomalies located on Line 40S and 55S at 10E. The same contours superimposed on the site plan (Figure 24) show how persistence correlates with the drum stack (2) and crushed drums (3), and discriminate between the wooden boxes containing mixed metal/asphalt/concrete (1) and steel casing over concrete vaults (7).

Figure 23. Persistence over time slice.

Figure 24. Persistence over site plan.

The very early time persistence available from the VETEM data may prove to be a useful additional discriminator for characterizing the shallow subsurface and objects buried in the subsurface.

In order to use persistence quantitatively, the system response should first be removed from the data.

5.4.3 Data Visualization

In addition to profile and individual time-slice images discussed above, it is possible to produce a sequence of time-slice images. Because VETEM data are highly sampled in time, it is possible to produce sequences of time-slice images from the data. When this is done, the resulting sequence of time-slices can be used to produce a “movie” from sequences of time-slice images using the AVI format. We have done this for some of the data from Pit 9, for example. These “movies” can also make differences in persistence visible.

After VETEM data are inverted using the University of Illinois DBIM, additional forms of visualization are possible. It is possible to show a series of depth, as opposed to time, slices with color indicating calculated conductivity. Alternatively, one may choose to display a 3-dimensional conductivity isosurface from the conductivities calculated by the DBIM inversion. We show an example of each of these types of visualizations in section 5.6.2 on the Pit 9 deployment.

5.5 VETEM Numerical Modeling

The University of Illinois at Urbana-Champaign developed the forward and inverse numerical modeling done in this project. Although the VETEM data have great utility in their own right, the full benefit of the finely sampled data can only be achieved when the data are inverted for depth. We consider the Distorted Born Iterative Method (DBIM) 1D inversion code developed by the University of Illinois, specifically for VETEM, to be one of the central achievements of this research. This code has been successfully applied to invert VETEM field data for depth at Pit 9, INEEL, as discussed below in the “VETEM Tests and Deployments” section. Although this code has not yet been implemented on a PC, it does run on modest sized UNIX workstations and is fast enough that in-the-field inversion of VETEM data is feasible.

5.5.1 Antenna Modeling

We have proposed an accurate model of wire antennas in free space, above or inside a lossy ground [20],[21], in which the current is assumed to flow on the surface of the wire and the testing is also performed on the surface. To replace the traditional delta-gap source, a more accurate source model was developed in this method using the Huygens' principle, and a variational formula of the input admittance was given. Comparing with other methods, this accurate model can provide much closer simulation results to the experimental data in both the current distribution and input admittance [21].

However, the accurate model will break down when the working frequency is very low, like most of the computational electromagnetic methods developed for electrodynamics [22]-[24]. The low-frequency breakdown problem is a consequence of the decoupling of electric and magnetic fields in Maxwell's equations right at zero frequency. Usually, the working frequencies of the VETEM system are very low to penetrate deeper in the lossy earth. Hence, we present a general method to analyze wire antennas above the lossy earth in this section, which will be valid from very-low frequency to microwave frequency. As we know, the electric field and magnetic field in Maxwell's equations will decouple completely at zero frequency. Such decoupling manifests that the electric current can be separated into two parts: a solenoidal (divergence-free) component and an irrotational (curl-free) component, which are complementary. At zero frequency, the two components also decouple completely, where the solenoidal current generates only magnetic field, and the irrotational current, which produces electric charge, generates only electric field. Therefore, such separation of current makes a natural Helmholtz decomposition.

The discrepant frequency-scaling requirement of the solenoidal and irrotational currents as the frequency tends to zero will cause numerical problems at very low frequencies. When the electric field integral equation (EFIE) governing the wire current is solved by the conventional method of moments, the contribution from the vector potential to the impedance matrix is much smaller than that from the scalar potential, and it will be lost during the numerical process due to the finite machine precision. Therefore, the electric current solved in this way only contains the irrotational current at very low frequencies, which approaches to zero. Obviously, this is not correct. The solution current should include both the solenoidal and irrotational components.

To solve the wire problem at very low frequencies, loop-tree basis functions are introduced, which can separate the contributions from the vector and scalar potentials in the impedance matrix. Such an impedance matrix is heavily unbalanced at very low frequencies. To balance the matrix elements, frequency normalization can be applied. After the frequency normalization, the contribution from the vector potential is uplifted and the contribution from the scalar potential is cut down, which finally have the same order. Finally, the normalized matrix equation has a good condition number and can be easily solved. Using the above method, the electric current on the transmitting loop and induced currents on the receiving loop can be accurately obtained. Numerical simulations verify the accuracy of the induced currents [25].

5.5.2 Forward Modeling

The geometrical structures of two typical VETEM systems are illustrated in Figure 25. In the orthogonal arrangement shown in Figure 25(a) [26],[27], the VETEM system contains a transmitting loop antenna, TX, a receiving loop antenna, RX, a lossy half space characterized by conductivity and relative permittivity, and buried objects which may be perfect conductors or lossy dielectrics. The source of the system is an input electric current driven by the transmitter, while the measured signal is the output current on the shorted-turn receiving loop at the receiver location.

(a) Orthogonal transmitter and receiver.

(b) Vertical gradiometer.

Figure 25. Two typical VETEM systems: (a) Orthogonal transmitter and receiver. (b) Vertical gradiometer.

In the vertical gradiometer shown in Figure 25(b) [28], the central square loop is the transmitter and other two loops are receivers. All the three loops are horizontally oriented. The two receiving loops are the same distance from the transmitting loop. We record the difference of electric currents on the two receivers, so as to eliminate the primary-field contribution from the transmitter.

From Figure 25(a), the coupling between the horizontal transmitter TX and the vertical receiver RX is very weak because they are orthogonal. However, the coupling between the horizontal transmitter and receivers in Figure 25(b) is very strong. Such coupling and the electric currents on the loop antennas can be accurately analyzed using the above wire antenna modeling.

When the electric currents on the loop antennas are obtained, we can easily determine the radiation electric field into the lossy earth using the half-space Green's function [29],[30],

which acts as the incident electric field on the buried scatterers. In the meanwhile, the primary magnetic field at the receiver location from the transmitter, the coupling magnetic field from the receiver, and the reflected magnetic field from the lossy earth can also be computed, which constitute the receiving current on the receiver. For the orthogonal arrangement shown in Figure 25(a), it is easily shown that both the primary and coupling fields are equal to zero; for the vertical arrangement shown in Figure 25(b), however, only the difference of the primary fields on the two receivers is zero. The coupling fields on the two receivers have a little difference because their vertical heights to the lossy ground are different.

The scattered magnetic field from the buried scatterers is very important for the VETEM modeling because it contains the information of the buried targets. To obtain the scattered field, we have to find the electric current distribution on the buried objects, which can be done by solving the electric field integral equation (EFIE). Usually, the method of moments (MOM) provides a best way to solve the EFIE numerically. However, the conventional MOM is very expensive because it needs N^3 computational complexity and N^2 memory requirement, where N is the total number of unknowns. To solve the scattering problem rapidly, some fast algorithms are investigated for different buried objects.

5.5.2.1 Buried Conducting Plates

If the buried scatterer is a conducting plate, we use the conjugate gradient method and fast Fourier transform (CG-FFT) to study the scattering problem. In the algorithm presented in [31], appropriate Green's functions have been derived so that the Galerkin's method can be applied to discretize the EFIE. The rooftop function is chosen for both basis and testing functions.

When the conducting plate is parallel to the air-ground interface, each term in discretized equations can be written as a two-dimensional (2D) cyclic convolution, which can be rapidly computed by the 2D FFT. Then a CG method is used to solve the discrete linear system. Due to the use of the FFT in handling cyclic convolutions related to Toeplitz matrices, the Sommerfeld integrals' evaluation for the buried scattering problem, which is usually time consuming, has been reduced to a minimum. Also, the memory required for this algorithm is only of order N , and the computational complexity is of order $N \log N$.

5.5.2.2 Buried Dielectric Objects

We choose the three-dimensional (3D) CG-FFT method to investigate scattering by buried dielectric objects [32]. In this method, the dielectric object is inscribed in a box, which is divided by 3D grids to perform the FFT. A symmetrical electric field dyadic Green's function has been derived in [32], from which the Galerkin method is easily used to discretize the EFIE. Again, rooftop functions are chosen as both basis and testing functions.

In the discretized equations, primary terms contributed by the primary electric field have a form of 3D cyclic convolution, which can be rapidly computed by 3D FFT. The reflected terms, however, are a 2D cyclic convolution in the xy plane and a one-dimensional cyclic correlation in z -direction, which can also be rapidly evaluated by a 3D FFT. Similar to the case of a buried conducting plate, the Sommerfeld integrals' evaluation has been reduced to a minimum due to the use of the FFT. Obviously, this is also an $N\log N$ algorithm.

5.5.2.3 Buried Conducting Objects

If the buried scatterer is a perfectly conducting object, the computational domain will be neither a rectangle nor a box, but a 3D surface. In this case, conventional CG-FFT methods cannot be used unless the computational domain is mapped to a plane. We choose the multilevel fast multiple algorithm (MLFMA) to study this problem [33], where the computational complexity and memory requirement are both of order $N \log N$.

As an example of the simulation results, we consider the scattering of a buried conducting plate. The sizes of transmitting and receiving loops are the same: 0.762 m (30 inches) in side length. For the orthogonal VETEM system, the distance between central points of transmitting and receiving loops is 2 m. The center of each antenna is 0.5334 m (21 inches) above the ground. In the Cartesian coordinate system shown in Figure 25(a), the transmitter-receiver system can move from left to right along the y -axis, keeping centers of the conducting plate and loop antennas to have the same x coordinate, where W denotes the distance between the center of the transmitter-receiver system and the vertical extension of the center of the buried plate. For the vertical gradiometer shown in Figure 25(b), all three loops have the same size: 0.762 m (30 inches) in side length. The transmitting loop is 0.8 m above the air-earth interface, and the receiving loops are 0.3 m and 1.3 m above the surface, respectively. The transmitter-receiver system can move from left to right along the y -axis, keeping centers of the conducting plate and loop antennas to have the same x coordinate, where d denotes the horizontal distance between the loop center and plate center. The relative permittivity of lossy ground is assumed to be 16, while the conductivity will change for different cases.

The input signal used in the simulation is a ramped pulse, whose waveform and frequency spectrum are displayed in Figure 26. From Figure 26(b), we clearly see that the bandwidth of the input signal is less than 10 MHz. In the following examples, all computations are performed in the frequency domain and an FFT is used to obtain the time-domain responses.

(a) Time-domain waveform.

(b) Frequency spectrum.

Figure 26. Simulated input signal and its frequency spectrum. (a) Time-domain waveform. (b) Frequency spectrum.

As we know, the numerical solution of Maxwell's equations at very low frequency is usually plagued by numerous problems. In the CG-FFT algorithm, the convergence is extremely slow when the working frequency is very low. As an example of a 2 m x 2 m conducting plate in the lossy earth, which is partitioned by 32 x 32 meshes, it requires 8,188 iterations to make the relative error 0.001 when $f = 0.02$ MHz. At the frequency of 5 MHz, it requires 600 iterations to reach the same relative error. If the working frequency is higher, however, the convergence of the CG-FFT algorithm can be very fast. For example, it needs only 35 iterations when $f = 100$ MHz for the same relative error. In order to obtain the time-domain responses rapidly, we start the CG-FFT simulation at the higher-frequency edge in the frequency spectrum, because it requires fewer iterations to converge. Using the final current distribution at this frequency as the initial value of the CG-FFT algorithm at the next frequency, the CG-FFT algorithm will converge very fast because the frequency increment is very small. We continue this procedure until the

simulation at the lowest frequency has been done. Therefore, it requires only a few iterations in the CG-FFT algorithm for all frequencies except the highest one, because very good initial values are provided.

Under the excitation of the input current shown in Figure 26, the reflected magnetic fields from the earth in the orthogonal VETEM system are illustrated in Figure 27 for different earth conductivities. From the above numerical results and other simulations, we notice that the reflected fields from the earth have the following properties:

Figure 27. Reflected magnetic fields at the receiver for different ground conductivities.

- When the ground conductivity increases, the amplitude of the earth response increases;
- When the ground conductivity increases, the slope of ramp in the earth response increases;
- When the ground conductivity is less than 10 S/m, the earth response has a significant tail. When it is larger than 10 S/m, the tail becomes smaller and smaller and disappears at around 50 S/m. After the ground conductivity is larger than 60 S/m, the earth response behaves like that of perfectly conducting ground.

Therefore, the reflected response is related to the ground conductivity, and we can estimate the conductivity from the response. A similar phenomenon occurs in the vertical gradiometer configuration. Besides the reflected field, there exists a coupling magnetic field in the vertical gradiometer. Because the coupling current on the lower receiver is weaker than that on the upper receiver, the difference of the coupling fields is a reversed ramp. On the other hand, the lower receiver is closer to the earth than the upper receiver, yielding an opposite ramp for the difference of reflected fields. Hence, the two ramps can be canceled to some extent, which reduces the clutter for scattered field [28].

To test the correctness of the scattered field, we have computed the time-domain responses for different sizes of conducting plates when $\sigma_b = 0.1$ S/m, $h_s = 1$ m and $d = W = 0$ for both VETEM systems, as shown in Figure 28. As a reference, we also give the scattered field of an infinite conducting plane in this figure, which is computed by a closed form formula in a one-dimensional (1D) model. From Figure 28, we clearly see that the scattered field becomes larger when the plate size increases. As the plate size reaches 4 m x 4 m, the scattered field is very close to that of infinite plane. When the plate size is 8 m x 8 m, the scattered field is nearly the same as that of infinite plane. Because the scattered fields of finite conducting plates are computed by the 3D CG-FFT algorithm and the frequency-hopping method, the agreement shows the validity of the modeling.

Figure 28. Scattered magnetic fields for different sizes of conducting plate: (a) Orthogonal VETEM system. (b) Vertical gradiometer.

Next, we compare simulation results to some measured data. The measured object was a wire-conductor mesh on the ground. When the height of the orthogonal transmitter-receiver system is 0.45 m and 1.34 m above the air-ground interface, we record the

measurement currents at the receiving loop. Because the measurement current is a convolution of total magnetic field at the receiver and a system function, the measurement data at 0.45 m are used to determine the system function. Considering the system function, simulation results from the numerical modeling is displayed in Figure 29 when the antenna-system height is 1.34 m. Compared with measurement data, the numerical model shows good agreement.

Figure 29. Comparison of the measurement data with simulation results.

Finally, we investigate the spatial-time domain property of the scattered field when the VETEM system moves around the buried objects. For the orthogonal VETEM system, the scattered-field responses of a 2 m x 2 m conducting plate are illustrated in Figure 30 when the earth conductivity $S_b = 0.5$ S/m. Here, the antenna-location axis represents the distance between the plate center and antenna-system center W . When the antenna center is at the left of the plate center, W is negative, or vice versa. From Figure 30, we clearly see that the strongest scattered value occurs around $W = 0$ in either case, where the center of a buried plate is located. Using this property, one can easily estimate the position of buried target from the spatial-time domain response. The other important property is that the strongest peak value has a positive time shift and the waveform becomes broader as the buried height and S_b increase, from which the buried depth and earth conductivity can be estimated.

(a) $h_s = 0.5$ m

(b) $h_s = 2.0$ m

Figure 30. Spatial-time domain scattered fields of the orthogonal VETEM system.

For the vertical gradiometer, Figure 31 illustrates the spatial-time domain scattered-field profiles of a 2 m x 2 m conducting plate when it is buried 0.5 m below the air-earth interface and $\mathbf{S}_b = 0.5$ S/m. From Figure 31, similar phenomenon occurs in this case. However, the strongest scattered value appears exactly at $d = 0$ because of the symmetrical property of the system.

(a) $h_s = 0.5$ m

(b) $h_s = 2.0$ m

Figure 31. Spatial-time domain scattered fields of the vertical gradiometer.

5.5.3 Inverse Modeling

The forward modeling provides the numerical simulations and physical interpretation of the VETEM systems. However, the inverse modeling seeks the reconstruction of the shape, position, and electrical properties of buried objects from the measurement data. Therefore, the inverse modeling is very important in the detection of buried targets. Since the inverse scattering problem is a complicated nonlinear one, which requires large computational resource and suffers from the non-stability, nonunique, and convergence problems, we investigated two simple algorithms for 2D objects using the distorted Born iterative method (DBIM) [34],[35], and diffraction tomographic algorithms for 2D and 3D objects [36],[37]. Next, we will briefly discuss these algorithms.

5.5.3.1 Single-Frequency Distorted Born Iterative Method

In inverse scattering to reconstruct buried objects, several simple models have been proposed by using the ground penetrating radar (GPR) technique without accounting for the air-earth interface. To build up more accurate models, a half space problem must be considered to represent the air-earth interface. Among the methods involving buried objects in half space or multi-layered media, the modified gradient approach and the diffraction tomographic scheme have been shown to be efficient algorithms. However, either only a single profile (permittivity or conductivity) can be reconstructed or the background is assumed to be lossless in these methods. To overcome the above difficulties, an efficient algorithm was presented [34] to reconstruct both the permittivity and conductivity profiles of 2D dielectric objects buried in a lossy earth, using the distorted Born iterative method (DBIM). The DBIM has been well designed and widely used in the homogeneous-space reconstruction, and here we have generalized it to solve the half-space problem.

In the single-frequency DBIM, we have to collect measurement data at different transmitter locations and different receiver locations to obtain enough information for detecting buried objects. Therefore, multiple transmitters and multiple receivers have to be used. Since the frequency is a constant throughout the algorithm, the permittivity and conductivity objects functions can be combined into a complex object function, which is being reconstructed. From the electromagnetic theory, a nonlinear relation between the measurement data and object function is derived. This nonlinear relation will be approximately linearized if the buried object is a weak scatterer compared with the background, which can be solved using the conjugate gradient method for the object function.

Usually, the earth parameters are first used as the initial guess of the object function. By solving the linear equation, an updated object function is obtained from the CG method. Then we use the updated object function as the new background, which is inhomogeneous and gives inhomogeneous medium Green's functions [34]. From the new background, the object function can be further updated. We repeat the above procedure until the error of object function is less than a tolerance error. To make the DBIM algorithm convergent, a Tikhonov regularization has been used to improve the condition of the relevant matrix [34].

In the DBIM algorithm, many forward solvers calls are invoked for all transmitter locations at each iteration step. Hence, the computational complexity of the fast solver will directly affect the inversion speed. In this algorithm, the CG-FFT method is applied as the fast forward solver. The Sommerfeld-like integrals involved are also evaluated using the FFT.

To test the validity of the single-frequency DBIM algorithm, we consider a numerical example, where the ground parameters are $\epsilon_b = 4$ and $\sigma_b = 0.005$ S/m. The reconstruction domain is a 2m x 2m square region, whose bottom side is 2.25 m below the air-earth

interface. This reconstruction domain contains $32 \times 32 = 1,024$ pixels. The measurement domain is 8 m on the air-earth interface centered about the reconstruction domain and 16 transmitter locations and 16 receiver locations are used. The scattered data are simulated using the CG-FFT algorithm by adding some random error. The original buried objects are two offset square dielectric objects. When the working frequency is 50 MHz, the reconstructed permittivity and conductivity profiles after the first iteration and fifth iteration are displayed in Figures 32(a) and (b), respectively. From Figure 32(a), the contrast of reconstructed profiles after the first iteration (the Born's approximation) is not accurate. In the permittivity profile, the image of lower object has a long tail. In the conductivity profile, however, the image of the lower object is not clear. After five DBIM iterations, the image quality of both permittivity and conductivity profiles has been notably improved: the long tail in the permittivity image has disappeared, and the lower object is much clearer in the conductivity image. Also, the contrast of reconstructed profiles is much more accurate than that in the Born approximation.

Figure 32. Reconstructed profiles of two offset dielectric objects using the single-frequency DBIM algorithm. (a) First iteration. (b) Fifth iteration.

5.5.3.2 Multiple-Frequency Distorted Born Iterative Method

In the single-frequency DBIM algorithm, we have to use multiple transmitters and multiple receivers to acquire enough information, which is expensive in the measurement. If we use multiple frequencies, however, the transmitter and receiver can have a fixed offset and be placed in a cart. We just move the cart to measure the scattered

fields at different transmitter-receiver locations. Therefore, the measurement system is easily set up for the multiple-frequency DBIM algorithm [38] and the measurement is easily achieved. However, two object functions, the permittivity profile and conductivity profile, have to be reconstructed since the frequency is changing in the algorithm. Hence we have to solve a larger matrix equation using the CG method. Also, at each DBIM iteration step described above, many forward solvers have to be called at all frequencies and all transmitter locations. Thus the multiple-frequency DBIM algorithm is slower than the single-frequency one [35].

As an example, we consider the reconstruction of the same buried objects used in Figure 32. The computational domain is a 2m x 2m region, whose bottom side is 2.25 m below the air-soil interface. This computational domain is divided into $32 \times 32 = 1,024$ pixels. The transmitters and receivers are located 0.5 m above the air-soil interface and 15 transmitter-receiver locations are used. The distance between the transmitter and receiver is fixed at 2 m. The measurement length is 10 m centered about the computational domain. The working frequency ranges from 0.5 MHz to 50.5 MHz and 11 frequency points are taken. Figure 33 illustrates the original and reconstructed profiles of two offset objects from the noisy measurement data. We clearly see that both the permittivity and conductivity images give good approximations to the real objects in the object locations and object contrast.

Figure 33. Original and reconstructed profiles of two offset dielectric objects using the multiple-frequency DBIM algorithm: (a) Original profile. (b) Reconstructed profile.

5.5.3.3 2D Diffraction Tomographic Algorithms

As shown above, two nonlinear algorithms have been developed using the distorted Born iterative method to detect the buried objects. Although fast solvers have been used to solve the forward problem, it still takes much CPU time to obtain the buried-object images for large objects because forward solvers must be called at every iteration. Generally, a VETEM system requires that the location of buried objects be determined in a few minutes using a portable computer at the site where the data are collected. For this purpose, a linearized inversion algorithm based on diffraction tomography is a good choice for on-site processing.

The principle of diffraction tomography is based on a linear relation between the spatial Fourier transform of the object function and the scattered field for weak scatterers, which was derived by Wolf in 1969. The DT method and its variations have been widely applied in the imaging of objects in a homogeneous space and geophysical problems. In most of the geophysical DT methods, however, the air-earth interface was not considered, leading to a distortion of the image. A notable improvement to the DT method for buried objects was proposed in [21], where the air-earth interface was taken into account. This is an excellent method and can be used for three-dimensional surveys. But there are two shortcomings in the method. First, an asymptotic formulation has been used to evaluate the Sommerfeld integrals, which is good for high-frequency methods like the GPR but invalid for low-frequency methods. Generally, a high-frequency field cannot penetrate deeply into a lossy earth. Second, the DT method in [39] was strictly derived from a lossless-medium assumption although it was heuristically modified for the lossy case.

To overcome the above problems, a novel DT algorithm is presented for imaging 2D dielectric cylinders buried in a lossy earth [36], where the air-earth interface is also taken into account. This algorithm can be used by a low-frequency system like the VETEM because the Sommerfeld-like integrals are considered in an exact way. In addition, this algorithm is directly derived based on a lossy background. Using the algorithm, all locations, shapes, and dielectric properties of the buried cylinders are accurately reconstructed under the low-contrast condition. For high-contrast targets, the algorithm can also be used to determine their location and approximate their dielectric properties. Due to the use of fast Fourier transforms in the implementation, this algorithm is very fast and quite robust with respect to the error of measurement data. The shortcoming of this algorithm is that more measurement data have to be collected to avoid the evaluation of Sommerfeld-like integrals.

As an example, we consider the reconstruction of three circular dielectric pipes which are diagonally located in the reconstruction domain, which is a 10m x 10m square region in the lossy earth and is divided into $64 \times 64 = 4,096$ pixels. The diameter of each pipe is 2.5 m. The transmitters and receivers are located 0.5 m above the air-earth interface. 64 transmitter locations and 64 receiver locations are used on the measurement domain which is 80 m long centered about the reconstruction domain. Therefore, the distance between TX and TX (or RX and RX) is 1.25 m. The working frequency ranges from 0.5 MHz to 60.5 MHz, then the corresponding wavelength varies from 300 m to 2.48 m in

the earth, which is suitable for reconstructing a dielectric cylinder with a diameter of 2.5 m. In this example, 60 frequency points are taken between 0.5 MHz and 60.5 MHz.

When the contrast of buried targets is much higher than the background, the original and reconstructed profiles of permittivity and conductivity are shown in Figure 34. From this figure, the shape of the image in both the permittivity and the conductivity has a distortion but the permittivity images have a good spatial resolution and provide accurate estimates of the contrast. In the conductivity image, the three buried pipes can also be clearly observed.

Figure 34. Original and reconstructed profiles from from the 2D diffraction tomographic algorithm.

5.5.3.4 3D Diffraction Tomographic Algorithms

Finally, we consider several efficient diffraction tomographic algorithms to reconstruct 3D buried dielectric objects using electric dipoles and magnetic dipoles as transmitters and receivers, respectively. In these algorithms, the air-earth interface has been taken into account and Sommerfeld integrals are exactly incorporated for full-information scattered data or evaluated by a general asymptotic-expansion approach for partial-information scattered data. Using these algorithms, the locations, shapes, and dielectric properties of buried objects can be well reconstructed under the low-contrast condition, and the objects can be well detected even when the contrast is high [37]. Due to the use of fast Fourier transforms to implement the problem, these algorithms are fast and quite tolerant to the error of measurement data, making it possible to solve realistic problems. Also, these algorithms are directly derived based on a lossy background and can be used by lower-frequency systems. Hence, objects deeply buried in the earth can be detected.

Figure 35 illustrates a reconstruction example of a buried dielectric cube, which is located at the center of a reconstruction domain: a 5m x 5m x 5m cubic region. The measurement domain is 20m x 20m above the air-earth interface. $64 \times 64 \times 64 = 262,144$ pixels are used to divide the reconstruction domain. The transmitter and receiver have a fixed offset of 0.5m, and measurement data are collected at $64 \times 64 = 4,096$ transmitter-receiver locations. The working frequency ranges from 1 MHz to 100 MHz. To view the reconstruction results, two central slices at $y = h_y/2$ and $z = -h_z/2$ are shown in the example.

Figure 35. Reconstruction results using electric dipoles from the 3D diffraction tomographic algorithm: (a) Permittivity profiles; (b) Conductivity profiles.

From Figure 35, we notice that high-resolution inversion results are obtained, where the corners of dielectric cube are clearly visible and the reconstructed permittivity gives a good approximation to the original value.

5.6 VETEM Tests and Deployments

5.6.1 Cold Test Pit

The Cold Test Pit (CTP) is a simulated waste pit at the INEEL. Figure 36 shows the location of the CTP and Pit 9, discussed below. The CTP consists of areas with different characteristics. In the Large Object Pit (LOP) portion of the CTP there are boxes, some containing metal, a drum stack, crushed drums, a steel tank, a concrete-filled steel pipe, unspecified drums, and steel casing over concrete vaults. The Calibration Cell (CC) is a

Figure 36. Pits 4, 9, and 10 are in the Radioactive Waste Management Complex at the Idaho National Engineering and Environmental Laboratory. The Cold Test Pit is just outside the RWMC.

smaller portion of the CTP. Discrete objects, such as boxes with metal in them, are in the CC. We have run some version of VETEM over the LOP on three occasions. The first was in 1995 during EMID, and we ran the original prototype with 10.5-inch diameter loop antennas [5]. The results were encouraging, but suggested the need for greater depth of investigation. In addition, at that time we had no ability to produce the areal time-slice displays that we can now produce.

In July 1998, we ran the LOP and the CC with the larger square loop antennas as a demonstration part of the EMSP research [40]. At that time we experimented with 2-m and 4-m spaced perpendicular antennas, and the overlapped antenna configuration. Figure 37 shows a time-slice view of data over the LOP using the 2-m spaced perpendicular antennas. Both antenna configurations produced comparable results over larger deeper objects, but the overlapped antennas proved superior in the detection of small objects. For this reason, the overlapped antennas were used over the CC. All but one of the listed targets in the CC were detected with VETEM. The unseen target is described as a 30-gallon plastic drum containing salt water. Figure 38 shows one time slice with an overlay of the nominal locations of the buried objects. It appears that the actual locations of the targets are slightly different from the nominal locations suggesting that the map coordinate system was slightly offset and rotated from the “as built” coordinates.

Figure 37. A VETEM time-slice image of the Large Object Pit portion of the Cold Test Pit from a 1998 survey with an overlay of documented burial objects. Also see Figure 24. An average waveform is displayed on the right.

Figure 38. A VETEM time-slice image of the Calibration Cell portion of the Cold Test Pit at INEEL produced using the overlapped antenna configuration. All but one of the documented objects was detected (see text).

The third VETEM trip to the CTP was made in August 2000. On this third trip we had not only more rigid and accurate loop antennas, but also the new linear/logarithmic receiver, and the system was towed behind the ATV with the RTK-GPS for positioning. Figure 39 shows the results from the LOP with coordinates now shown in the Universal Transverse Mercator (UTM) system.

Figure 39. A time-slice image of the LOP portion of the CTP. The response from some of the weaker targets may be stronger as compared to Figure 37.

5.6.2 Pit 9

The first application deployment of the VETEM system was a survey of Pit 9 in the Radioactive Waste Management Complex (RWMC), INEEL (Figure 40). Objectives for the survey were to produce maps of Pit 9 that would be as spatially accurate as possible and that would include estimations of depth to buried conductive objects. The data were used to aid in placement of stainless steel tubes for nuclear logging adjacent to certain objects in Pit 9 prior to remediation of portions of Pit 9. We surveyed the majority of Pit 9 with VETEM with a line spacing of 1 m and lines run east to west. There was a particular area of interest where lines were run in two directions and where the line spacing was reduced. A VETEM image of Pit 9 is shown in Figure 41. Figure 42 shows a series of depth panels at 0.5-m increments showing the conductivities calculated from the University of Illinois DBIM code. The higher conductivities are mapped into hotter colors. Figure 43 shows a 3-dimensional volume view created by mapping a surface corresponding to a constant conductivity. The conductivity was chosen at a relatively high value. Most of the volume inside the isosurface probably contains buried metal objects. An exception is an area in the southeast dogleg area just off Pit 9 (see Figure 41). In this area the high calculated conductivity is probably due to basalt that is near the surface. This feature can be distinguished from buried metal objects by observing that the signal responses for the two cases decay with different time constants.

Figure 40. The cart was still towed by the logging truck cable at this time (1998).

Figure 41. This time-slice image of Pit 9 shows higher amplitudes in hotter colors. High amplitude responses in this image indicate buried metal objects.

Figure 42. These relative conductivity slices of Pit 9 are depth slices rather than time slices and are derived from the results of the University of Illinois DBIM inversion. Note that the top slices show no highly conducting objects as is reasonable in the Pit cover.

Figure 43. This 3D volume encloses regions that exceed a conductivity threshold calculated using the University of Illinois DBIM inversion. Most of the volume includes buried metal. An exception is the “arm” in the lower right. The explanation is near surface basalt. Time decay rates can distinguish between the geologic and buried metal responses.

5.6.3 Pits 4 and 10

Pits 4 and 10 and the reoccupation of the CTP at INEEL are the most recent applications of VETEM [41]. Pits 4 and 10 are much larger in area than Pit 9. Calculations indicated to us that we needed to convert to an ATV-towed version of VETEM (Figure 44) in order to cover Pits 4 and 10 with finely spaced data in a reasonable amount of time. The new towed version of VETEM has been discussed in an earlier section.

Figure 44. The All-Terrain-Vehicle made the survey of Pits 4 and 10 possible.

Figure 36 shows the location of the RWMC at INEEL. Not all areas on the grid could be reached because of buildings and other obstacles. Figure 45 shows the lines actually run with VETEM with each day's data indicated in a unique color. Figure 46 shows a time-slice view of VETEM data over Pits 4 and 10. The most highly conducting areas are in the hottest colors, as is our usual display convention. Inversion of the data using the University of Illinois DBIM code is underway. When the inversions are completed, a final report will be written.

Figure 45. This figure shows the boundaries of Pits 4 and 10 in the RWMC at INEEL and the lines run on those pits with VETEM. Buildings and other obstacles prevented complete coverage. Each day's coverage is shown in a unique color.

Figure 46. This figure shows a time-slice amplitude image of VETEM data taken over Pits 4 and 10 at the RWMC at INEEL in 2000. This image is formed from raw data taken over several days. No leveling has been done on the data demonstrating the relative stability of the VETEM system. “Tearing” in the data is minor.

5.6.4 Former Munitions Foundry Site

While giving a demonstration at the Denver Federal Center of VETEM procedures for development of a required Health and Safety Plan in connection with our planned survey of Pit 9 at INEEL, we noticed unusually large signals. They were so large that we initially thought something was wrong with the system. We found, however, that we had set up the system on the site of a former WWII artillery ammunition foundry. We decided to survey the site (Figure 47) with VETEM and found the results little short of stunning [42]. Figure 48 shows one image produced from VETEM data collected at the site. This site has the advantage of strong conductivity contrasts plus regular features that are clearly man-made. This site has become a favorite for tests of various geophysical instruments designed for subsurface imaging. So far, the VETEM images provide the clearest images we have yet seen of the buried structures under the ground at this site and are now the benchmarks to which all other images are compared. In addition, the VETEM images from various time slices look somewhat different, with some features prominent at some, but not all, times, and others persisting throughout [42]. Although some have suggested that it was VETEM’s high spatial data density that provided superior images, other instruments used at similar spatial data densities did not produce results as clear as the VETEM images. We attribute the clarity, in part, to the spectral content of the VETEM pulses.

Commercial GPR has also been tried over this site without much success, but high frequency antennas were used and the high electrical conductivity (about 67 mS/m to about 333 mS/m) makes this site quite difficult for GPR [1]. We also did some very preliminary work with the VETEM electric field dipole antennas and, though the results were not as clear as with the loop antennas, we think further investigations over that site coupled with more modeling of propagation in dispersive media might be fruitful [2],[3].

Figure 47. The dark building in the center of the left panel was a World War II munitions foundry. Photo, circa 1945, supplied by Rene Valero, General Services Administration. The right panel shows the Building 20 east parking lot and field on the site of the World War II munitions foundry building. Photo (1998) by Dave Campbell, USGS.

Figure 48. This VETEM time-slice image of a former munitions foundry site shows subsurface structures with great clarity. The three large ring-like features may be associated with subsurface oil tanks or tank foundations left in place when the building was removed.

5.7 Assessing VETEM

Our assessment of VETEM cannot be exhaustive, in part, because there are many conceivable applications that we have not yet encountered. Therefore we base our assessment largely on our experience at waste pits at the INEEL and results from the former munitions foundry site at the Denver Federal Center. VETEM cannot answer all geophysical subsurface imaging questions, nor do we claim that it is the best EM instrument to choose for every application. However, images produced using VETEM at the DFC former foundry site have exceeded those we produced with a number of alternative EM instruments, and our images of pits at INEEL compare quite well to other EM and magnetic survey images. VETEM is a very good tool for certain types of applications, especially so when the data are inverted using the University of Illinois DBIM inversion algorithm.

We are especially pleased that our time-domain data may generally be successfully inverted. Some had suggested to us that although VETEM might find anomalies, our time-domain data would not be accurate enough to produce useful inversions. It appears now that this view was too pessimistic.

We think VETEM could be extended in a number of ways to make it even more useful. We will mention some of those near the end of this report.

5.7.1 System Capabilities

VETEM has many strong points, including:

- fast non-stop profiling, similar to GPR,
- real-time data display, similar to GPR,
- operation in a part of the frequency spectrum that is not commonly used,
- full waveform recording to permit extraction of maximum information from data,
- real-time full waveform averaging for fast signal-to-noise ratio improvement,
- flexibility with respect to spectral content of waveforms,
- flexibility with respect to antenna types and configurations and,
- accurate positioning using RTK-GPS.

5.7.2 Data Processing and Visualization

We have also implemented a number of advanced data visualization capabilities including:

- in-the-field preprocessing,
- profile views of the data along any chosen line,
- time-slice views of either raw or residual data,
- subsurface induced current persistence mapping,
- time-slice “movies”,
- depth slice visualization, and
- 3-dimensional conductivity isosurfaces after inversion.

5.7.3 VETEM Field Data

We have seen images produced with commercial EM and magnetometer systems at Pit 9. VETEM time-slice images of Pit 9 are comparable, in many respects, to the images produced with commercial systems. If the objective is to horizontally locate buried metal targets VETEM appears to be about on a par with the best commercial EM units designed for metal detection. However, the full waveform data produced by VETEM responds to both buried metal and geologic conductivity contrasts and the two can be distinguished from each other based on the persistence or time decay of the VETEM waveforms, at least in the cases we have examined to date. Thus, if the objective is broadened to include not only response to buried metal, but shallow earth conductivity contrasts as well, VETEM data offer advantages.

At the former foundry site, discussed previously, commercial magnetic and electromagnetic systems have been used, as well as VETEM. Although images produced using different instruments reveal this or that subsurface feature especially clearly, the VETEM images are the best overall, and have become the benchmarks for that site. Since different commercial systems were operated by various individuals, including vendor representatives, professional USGS geophysicists, and student geophysicists, we did not have control over all data acquisition practices and thus cannot guarantee that all instruments were operated in such a way as to produce the most favorable results. (In almost all cases each instrument was operated according to the manufacturer's recommendations, however). Therefore, we do not show comparison images in this report. We cite two published papers, however [1], [42]. Additional geophysical surveys at this DFC site will no doubt be reported in future papers. It appears to us that the part of the electromagnetic spectrum in which we operated VETEM was a good match for the DFC former foundry site. We attribute the superior quality of the VETEM images, at least in part, to a good spectral match, and not merely to our high spatial data density.

Although other EM instruments can be run with a GPS, few use this capability routinely. The VETEM system now includes an integral RTK-GPS, so in this respect the current VETEM system also offers superior horizontal positioning.

5.7.4 Inversion of VETEM Data

Although the VETEM field data themselves offer advantages as compared to conventional EM data, a central VETEM strength is the ability to invert VETEM data to produce relatively high resolution maps of electrical conductivity versus depth. VETEM is not completely unique in this regard, and other investigators are working on inversion routines that may permit similar inversions of data produced with other EM instruments. Nevertheless, at present, the inversions of Pit 9 data from VETEM data using the University of Illinois code appear to offer superior vertical resolution. Coupled to accurate horizontal positioning, inversion can provide 3D information that may be needed for certain applications.

5.7.5 Depth of Investigation

As with many things in geophysics, it is not possible to provide a single answer to the question, “How deep can you see with VETEM?” Too many variables are involved, such as the host soil conductivity, capping material conductivity and thickness, the electrical conductivity contrasts between soil and buried materials, and the size of buried objects. We did make a series of improvements to various elements of the system such as antennas, transmitters, receivers, and many of these improvements appear to have added significantly to the depth capability of the system.

Our original goal, however, was to image the subsurface from 0 to about 5 m deep. One reason for this goal was that many waste burial pits are about this deep. Another reason was that many existing TDEM systems were considered to give poor resolution in the first 5 m of depth. The data sets that we have include tests at the INEEL Cold Test Pit where depths to various objects in the LOP and Calibration Cell may be known. However, we do not have depth information. The University of Illinois informally estimated that our Pit 9 data allowed reliable conductivity inversion to about 4-m depth. Since that time we have added a new receiver and more rigid antennas, so our current capability might be somewhat better. It is clearly possible to further extend the depth capability of the VETEM system as we will mention later.

5.7.6 System Stability

In-the-field calibration once or twice a day provides a measure of the system stability. Factors that might affect VETEM include thermal drifts in electronic and fiber-optic circuits, antenna mechanical shifting, optical attenuation in the fiber-optic data link due to dust in the optical connectors, and low battery voltage should the batteries be run down too far and the voltage regulators loose regulation. No system is completely stable, but every time we have taken VETEM to the field it has performed better and has been more stable than the previous time. The cart and antennas are far more rigid than previously, so antenna movement is much less. The new receiver is also designed so that the battery pack can be removed without disconnecting the fiber-optic connectors. This is a considerable improvement, because dust particles can easily get onto connector ends when the wind is blowing (which seems to be most of the time at INEEL). Our field procedure includes blowing off the connector ends with an air can immediately prior to connecting the fiber-optic cables. We also now use ST type connectors that are spring loaded and superior in consistency to the SMA type connectors we once used. As evidence of the stability of VETEM data, we note that the data displayed from Pits 4 and 10 at INEEL (Figure 46) are raw data with no leveling.

6. RELEVANCE, IMPACT, and TECHNOLOGY TRANSFER

a. Impact of results on DOE environmental management problems

This research has impact in characterization, monitoring, and remediation activities. It has already been applied to imaging the contents of waste pits and might be applied to a wide variety of applications such as:

- Detection of buried objects such as drums and boxes at shallow depth,
- Imaging and characterization of shallow geologic structure that may control hydraulic flow and transport of toxic chemicals,
- Identification and mapping of pits and trenches,
- Monitoring landfill stabilization grouting procedures,
- Assessment of the integrity of covers,
- Location of buried utilities,
- Monitoring pollutants.

b. Benefit of results to improving cleanup technologies: cost, risk, and schedule

In any situation where significant active intervention is required in the shallow subsurface, accurate 3D imaging could save hundreds of thousands to millions of dollars by pinpointing the location and partially characterizing the nature of subsurface wastes. Avoidance of accidental penetrations of hazardous chemical or radiological waste can greatly reduce risk to workers and avoid costly shutdowns with resultant schedule slippage. The improvements in shallow subsurface imaging accomplished in this research, particularly improving the ability to image the depth dimension, are a very significant potential benefit to cost, risk, and schedule.

c. Extent to which results bridge the gap between research and application

This research has spanned the entire spectrum from basic electromagnetic modeling research, to instrument development, to application. VETEM deployments to Pit 9, Pit 4, and Pit 10, in the RWMC at INEEL described in section 5.6 of this report demonstrate significant applications. We hope for more such applications so that this research can achieve the fullest possible return for the Department of Energy Environmental Management Program.

d. Relevance of research to other laboratories

Many, if not all, DOE sites have disposed of wastes in subsurface pits or trenches. In any case where these pits or trenches need to be imaged, VETEM might help. We mention as examples of sites that are known to have subsurface disposal sites:

- Savannah River
- Rocky Flats
- Los Alamos
- Lawrence Livermore
- Sandia

- Oak Ridge
- Fernald
- Weldon Springs
- Paducah
- Idaho (INEEL)
- Hanford

This is a random short list. It could be greatly expanded.

e. Utility of finding to future technologies

Our findings are in both numerical modeling and instrumentation. The numerical modeling research clearly has made some breakthroughs in electromagnetic modeling at low frequencies with utility for electromagnetic imaging. Our instrument development also shows the utility of operating in a portion of the electromagnetic spectrum that is intermediate between those of typical electromagnetic induction instruments and ground penetrating radar. In addition, we have demonstrated the utility of rapid signal-to-noise enhancement by real-time averaging of entire waveforms. The 1D Distorted Born Iterative Method inversion algorithm has potential utility for VETEM and other instruments.

f. Impact on collaborators

VETEM data were used to aid the placement of stainless steel tubes for nuclear logging in Pit 9 and more recently in parts of Pit 4 and Pit 10 at the INEEL. The nuclear logging, in turn, is being done to positively identify particular radioactive buried waste locations within the pits in anticipation of at least partial remediation of leaking waste. Surface geophysical data such as ours is important so that the best locations for the tubes may be selected.

g. Advances in understanding

This research has advanced our understanding of the potential for high-resolution 3D electromagnetic subsurface imaging through conductive soils. Though the problem is not an easy one, either from an instrument or numerical point of view, and will always depend on the electromagnetic properties of the earth, we now see that the use of a time-domain instrument operating in the 10's of kHz through the low MHz part of the electromagnetic spectrum can sometimes produce results not obtained before.

h. Further work necessary to realize ultimate goal

To fully achieve what we think can be done using the type of instrumentation and numerical methods we have developed for VETEM, we would need to do the following additional work that was proposed [43], but not funded:

- further increase the depth of investigation of the instrument,
- add arrays of antennas to allow more efficient and accurate inversion of field data,
- develop multi-dimensional inversions,

- develop a borehole version of VETEM for investigations at great depth, and
- couple VETEM data to other geophysical and geohydrologic investigations.

i. Interest in work expressed by other agencies and media

This research has attracted interest from the following agencies, in addition to DOE:

- DOD,
- EPA,
- Law Enforcement
- City and County of Denver

In addition, several instrument manufacturers and geophysical companies have followed our work with some interest. We have had contacts from two instrument manufacturers who have expressed interest in a CRADA for VETEM or a VETEM derivative. Most of these contacts have made it clear that they were more interested in the Unexploded Ordnance (UXO) problem and wanted to modify VETEM to optimize it for such applications. We have not entered into any agreements at this time.

7. PRODUCTIVITY

This research accomplished the major goal of enhancing the state-of-the art of shallow subsurface electromagnetic imaging in conductive soils. We exceeded our intended goals in terms of applications and were compelled by those applications to focus on making the prototype truly field-worthy and to integrate a Real-Time Kinematic Global Positioning system into the VETEM system. That effort has been rewarded by our ability to produce spatially accurate data.

The modeling by the University of Illinois has broken new ground and may substantially impact the practice of low-frequency electromagnetic modeling. The development of the 1D DBIM inversion code and its successful application to real field data is gratifying. Only in our intention to implement that code on a PC for in-the-field inversion did we fall slightly short. The code is running on a modest workstation, however, and is fast enough that in-the-field inversion of modest sized data sets is feasible.

8. PERSONNEL SUPPORTED

A. USGS

This research provided part-time support for the following personnel at the USGS:

David L. Wright, Lead Principal Investigator and Electronics Engineer

David V. Smith, Geophysicist

Jared D. Abraham, graduate student, Geophysics, Colorado School of Mines. Upon completion of the M.S. degree Mr. Abraham was hired as a geophysicist by the USGS.

S. Raymond Hutton, Electronics Engineer

Richard T. Smith, undergraduate student, Electrical and Computer Engineering,
University of Colorado at Denver

E. Kent Bond, undergraduate student, Electrical and Computer Engineering, University
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9. PUBLICATIONS

Abraham, J.D., D.V. Smith, and D.L. Wright, 2001, A survey of waste pits at the Idaho
National Engineering and Environmental Laboratory using the new USGS
prototype ATV towed VETEM platform: Proceedings of the Symposium on the
Application of Geophysics to Engineering and Environmental Problems
(SAGEEP), 2001, March 4-7, 2001, Denver, CO. (*in press*).

Aydiner, A.A., W. C. Chew, T. J. Cui, D. L. Wright, D. V. Smith, and J. D. Abraham,
2001, "3D imaging of large scale buried structure by 1D inversion of very early
time electromagnetic (VETEM) data," IEEE Trans. on Geoscience and Remote
Sensing, vol. 39, no.4, July 2001 (*in press*).

Cui, T.J. and W.C. Chew, 1998 "Efficient evaluation of Sommerfeld integrals for TM
wave scattering by buried objects," J. Electromagnetic Waves Appl., vol. 12, pp.
607-657, 1998.

Cui, T.J. and W.C. Chew, 1998 "Efficient method for the near-field detection of buried
dielectric and conducting objects," Electromagnetics, vol. 18, pp. 555-573, no.6,
1998.

Cui, T.J. and W.C. Chew, 1999, "Fast evaluation of Sommerfeld integrals for EM
scattering and radiation by three-dimensional buried objects," IEEE Trans. On
Geoscience and Remote Sensing, vol. GE-37, pp.887-900, no.2, Mar. 1999.

Cui, T.J. and W.C. Chew, 1999, "Fast algorithm for electromagnetic scattering by buried
conducting plates of large size," IEEE Trans. on Antennas and Propagation, vol.
47, pp. 1116-1118, no.6, Jun. 1999.

- Cui T.J. and W. C. Chew, "Novel diffraction tomographic algorithm for imaging two-dimensional targets buried under a lossy earth," IEEE Trans. on Geoscience and Remote Sensing, vol. 38, pp. 2033-2041, no. 4, Part 2, July 2000.
- Cui, T.J. and W.C. Chew, 1999 "Frequency-spatial domain inverse scattering of two-dimensional dielectric objects buried under a lossy earth," Research Report, Electromagnetics Laboratory, University of Illinois at Urbana-Champaign, No. CCEM-19-99, July 1999; also submitted to IEEE Trans. on Microwave Theory and Techniques.
- Cui, T.J. and W.C. Chew, 1999, "Fast algorithm for electromagnetic scattering by buried 3D dielectric objects of large size," IEEE Trans. on Geoscience and Remote Sensing, vol. GE-37, no.5, pp. 2597-2608, Sep. 1999.
- Cui, T.J. and W.C. Chew, 2000, "Modeling of arbitrary wire antennas above ground," IEEE Trans. on Geoscience and Remote Sensing, vol. GE-38, no.1, Part 2, Jan. 2000.
- Cui, T.J. and W.C. Chew, 2000, "Three-dimensional linearized inverse scattering methods for dielectric objects buried in a lossy earth," Research Report, Electromagnetics Laboratory, University of Illinois at Urbana-Champaign, No. CCEM-08-00, Feb. 2000; also submitted to IEEE Trans. on Antennas and Propagation.
- Cui, T.J. and W.C. Chew, 2000, "Accurate Model of arbitrary wire antennas in free space, above or inside ground," IEEE Trans. on Antennas and Propagation, vol. AP-48, no. 4, Apr. 2000.
- Cui, T.J., W. C. Chew, A. A. Aydinler and S. Y. Chen, "Inverse scattering of 2D dielectric objects buried in a lossy earth using the distorted Born iterative method," IEEE Trans. on Geoscience and Remote Sensing, vol. 39, no.1, Jan. 2001 (in press).
- Cui, T.J., W.C. Chew, A. A. Aydinler, D. L. Wright, D. V. Smith, and J. D. Abraham, 2000, "Numerical modeling of an enhanced very early time electromagnetic (VETEM) prototype system," IEEE Antennas and Propagation Magazine, vol. 42, no. 4, Apr. 2000.
- Cui, T.J., and W. C. Chew, "Accurate analysis of wire structures from very-low frequency to microwave frequency," IEEE Trans. on Antennas and Propagation, vol. AP-49, no. 4, Apr. 2001 (in press).
- Cui, T.J., W. C. Chew, A. A. Aydinler, D. L. Wright, D. V. Smith, and J. D. Abraham, "An Addendum to 'Numerical modeling of an enhanced very early time electromagnetic (VETEM) prototype system'," IEEE Antennas and Propagation Magazine, vol. 42, no. 3, pp. 54-57, June 2000.

- Cui, T.J., W. C. Chew, A. A. Aydinler, D. L. Wright, D. V. Smith, and J. D. Abraham, "Detection of buried targets using a new enhanced very early time electromagnetic (VETEM) prototype system," IEEE Trans. on Geoscience and Remote Sensing, to be published.
- Cui, T.J. and W. C. Chew, "Diffraction tomographic algorithms for the detection of three-dimensional objects buried in a lossy half space," Research Report, Electromagnetics Laboratory, University of Illinois at Urbana-Champaign, No. CCEM-6-00, February 2000.
- Smith, D.vonG, Wright, D.L., Abraham, J.D., 2000, Advances in Very Early Time Electromagnetic (VETEM) System Data Analysis and Image Processing: Proceedings of the Symposium on the Application of Geophysics to Engineering and Environmental Problems, Arlington, VA, February 20-24, 2000, p. 469-475.
- Wright, D.L., Smith, D.V., Abraham, J.D., Hutton, R.S., Bond, E.K., Cui, T.J., Alaeddin, A.A., and Chew, W.C., 2000, Imaging and modeling new VETEM data, Proceedings of the 8th International Conference on Ground Penetrating Radar, Gold Coast, Queensland, Australia, May 23-29, 2000, p. 146-150.
- Wright, D.L., Smith, D.V., and Abraham, J.D., 2000, A VETEM survey of a former munitions foundry site at the Denver Federal Center: Proceedings of the Symposium on the Application of Geophysics to Engineering and Environmental Problems, Arlington, VA, February 20-24, 2000, p. 459-468.
- Wright, D.L., Smith, D.V., Abraham, J.D., Smith, R.T., Cui, T.J., and Chew, W.C., 1999, New field and modeling results from a simulated waste pit using the enhanced very early time electromagnetic (VETEM) prototype system: Proceedings of the Symposium on the Application of Geophysics to Engineering and Environmental Problems, Oakland, CA, March 14-18, 1999, p. 811-820.
- In addition, two reports are in preparation on the application of VETEM to Pit 9, Pit 4 and Pit 10 and the Cold Test Pit at INEEL.

10. INTERACTIONS

1. EMSP National Workshop (Poster presentation), Chicago, 1998.
2. EMSP National Workshop (Poster presentation), Atlanta, 2000.
3. International Union of Radio Science 26th General Assembly, Toronto, Canada, August 13-21, 1999. (Papers by U. of Illinois and USGS).
4. Symposium on the Application of Geophysics to Engineering and Environmental Problems, 1998 (Papers 1999, 2000, 2001)
5. International Conference on Ground Penetrating Radar, 1998, Lawrence, Kansas. (paper).
6. International Conference on Ground Penetrating Radar, 2000, Goldcoast, Australia. (paper).

The Principal Investigator has also attended numerous DOE EM meetings including:

7. SCFA Midyear Review Meeting, 1999, Augusta, GA
8. SCFA Midyear Review Meeting, Albuquerque, NM
9. Long-Term Stewardship Meeting, 2000, Cincinnati, OH.
10. Technical Information Exchange Meeting, 2000, Augusta, GA.

11. TRANSITIONS

To this point there have been no official transitions, but we have had two deployments at the INEEL, mentioned above.

12. PATENTS

No patents have been applied for as a result of this research.

13. FUTURE WORK

Although our renewal proposal was not successful, we are finishing work for INEEL and looking for similar opportunities at other sites.

14. ACKNOWLEDGEMENTS

Work in a DOE radioactive waste facility entails considerable time, effort, and expense, both on the part of the USGS VETEM crew and on the part of the site contractor and contractor personnel. In order for a deployment to happen, someone at the site has to be convinced that the work offers significant benefit and then function as an advocate to make it happen. We thank George Schneider of DOE and Aran Armstrong (formerly of DOE) for their interest and advocacy. They made it possible for us to work at Pit 9 and Pits 4 and 10 with practical support and supplemental funding for field work under Inter-agency agreement DE-AI07-92ID13207. Lockheed Martin Idaho, Bechtel Idaho, and other contractor personnel provided invaluable support. Particularly important to our on-site work were David Wilkins, Jim Pletscher, Tim Green, Kelly Wooley, and Jason Casper. Corner coordinates for Pit 4 and Pit 10 at INEEL were provided to us by Ken Beard. Without their support, our work at INEEL could not have happened.

15. DISCLAIMER

The use of trade, product, or firm names is for descriptive purposes only and does not imply endorsement by the U.S. Government.

16. LITERATURE CITED

1. Campbell, D. L., Beanland, S., Lucius, F.E., Powers, M.H., 2000, Magnetic and GPR surveys of a former munitions foundry site at the Denver Federal Center: Proceedings from the Symposium on the Application of Geophysics to Engineering and Environmental Problems (SAGEEP 2000), Arlington, VA, Feb. 20-24, p. 453-458
2. Wright, D.L., Smith, D.V., Abraham, J.D., Hutton, R.S., Bond, E.K., Cui, T.J., Alaeddin, A.A., and Chew, W.C., 2000, Imaging and modeling new VETEM data, Proceedings of the 8th International Conference on Ground Penetrating Radar, Gold Coast, Queensland, Australia, May 23-29, 2000, p. 146-150.
3. Powers, M.H. and Olhoeft, G.R., 1995, GPRMODV2: One-dimensional full waveform forward modeling of dispersive ground penetrating radar data version 2: U.S. Geological Survey, Open File Report 95-58, Denver, Colorado, 41p.
4. Pellerin, L., Alumbaugh, D.L., and Pfeifer, M.C., 1997, The electromagnetic integrated demonstration at the Idaho National Engineering Laboratory Cold Test Pit: Proceedings of the Symposium on the Application of Geophysics to Engineering and Environmental Problems, Reno, NV, March 23-26, 1997, p. 725-734.
5. Wright, D.L., Grover, T.P., Labson, V.F., and Pellerin, L., 1996, The very early time electromagnetic (VETEM) system: first field test results: Proceedings of the Symposium on the Application of Geophysics to Engineering and Environmental Problems (SAGEEP '96), Keystone, CO, April 28-May 2, 1996, p. 81-90.
6. Stewart, D.C., W.L. Anderson, T.P. Grover, and V.F. Labson, 1990, A new instrument and inversion program for near-surface mapping - High frequency EM sounding in the frequency range of 300 kHz-30MHz, in Proceedings of 60th Annual Meeting: Society of Exploration Geophysicists, v. 60, p. 130.
7. Sternberg, B.K., 1999, A new method of subsurface imaging- the LASI high frequency ellipticity system: Part 1. System design and development: Journal of Environmental and Engineering Geophysics, v. 4, no. 4, p. 197-214.
8. Sternberg, B.K., Thomas, S.J., and Birken, R.A., 1999, A new method of subsurface imaging- the LASI high frequency ellipticity system: Part 2. Data processing and interpretation: Journal of Environmental and Engineering Geophysics, v. 4, no. 4, p. 215-226.
9. Sternberg, B.K. and Birken, R.A., 1999, A new method of subsurface imaging- the LASI high frequency ellipticity system: Part 3. System tests and field surveys: Journal of Environmental and Engineering Geophysics, v. 4, no. 4, p. 227-240.

10. Li, K.H., 1997, High frequency electromagnetic impedance measurements for characterization, monitoring, and verification efforts, EMSP project 60328, continued as project 73776.
11. Newman, G.A., and Nichols, E., 1999, High frequency electromagnetic impedance imaging for vadose zone and groundwater characterization, EMSP Project 70220.
12. Wright, D.L., Hodge, S.M., Bradley, J.A., Grover, T.P., and Jacobel, R.W., 1990, A digital low-frequency, surface profiling ice radar system: *Journal of Glaciology*, v. 36, no. 122, p. 112-121.
13. Wright, D.L., Bradley, J.A., and Hodge, S.M., 1989, Use of a new high-speed digital data acquisition system in airborne ice-sounding: *IEEE Transactions on Geoscience and Remote Sensing*, v. GE-27, no. 5, p. 561-567.
14. Precision Instruments, Inc., Model 9826 User's Manual, P.O. Box 11235, Knoxville, TN 37939.
15. Tektronix, Inc., Model CT-1/CT-2 Current Transformer Instruction Manual, P.O. Box 1000, Wilsonville, OR 97070-1000.
16. Research Systems, Inc., 2000, IDL version 5.4, 4990 Pearl East Circle, Boulder, CO 80301.
17. Smith, D.vonG, Wright, D.L., Abraham, J.D., 2000, Advances in Very Early Time Electromagnetic (VETEM) System Data Analysis and Image Processing: *Proceedings of the Symposium on the Application of Geophysics to Engineering and Environmental Problems*, Arlington, VA, February 20-24, 2000, p. 469-475.
18. Corpscon, Version 5.11.08, 1997, U.S. Army Corps of Engineers, Topographic Engineering Center, Alexandria, Virginia, 22315-3864.
19. Nabighian, M.N., 1996, Time domain electromagnetic prospecting methods *in* *Electromagnetic Methods in Applied Geophysics – Applications*, Part A and Part B, Society of Explorations Geophysicists, P.O. Box 702740, Tulsa, OK 74107
20. T. J. Cui and W. C. Chew, "Modeling of arbitrary wire antennas above the ground," *IEEE Trans. on Geoscience and Remote Sensing*, vol. GE-38, no.1, Part 2, Jan. 2000.
21. T. J. Cui and W. C. Chew, "Accurate Model of arbitrary wire antennas in free space, above or inside ground," *IEEE Trans. Antennas Propagat.*, vol. AP-48, no. 4, Apr. 2000.

22. E. Arvas, R. F. Harrington and J. R. Mautz, "Radiation and scattering from electrically small conducting bodies of arbitrary shape," *IEEE Trans. on Antennas and Propagation*, vol. 34, pp. 66-77, Jan. 1986.
23. M. Burton and S. Kashyap, "A study of a recent, moment-method algorithm that is accurate to very low frequencies," *Applied Computational Electromagnetic Society Journal*, vol. 10, no. 3, pp. 58-68, Nov. 1995.
24. W. Wu, A. W. Glisson and D. Kajfez, "A study of two numerical solution procedures for the electric field integral equation at low frequency," *Applied Computational Electromagnetic Society Journal*, vol. 10, no. 3, pp. 69-80, Nov. 1995.
25. T. J. Cui and W. C. Chew, "Accurate analysis of wire structures from very-low frequency to microwave frequency," *IEEE Trans. on Antennas and Propagation*, vol. AP-49, no. 4, Apr. 2001 (in press).
26. T. J. Cui, W. C. Chew, A. A. Aydiner, D. L. Wright, D. V. Smith, and J. D. Abraham, "Numerical modeling of an enhanced very early time electromagnetic (VETEM) prototype system," *IEEE Antennas and Propagation Magazine*, vol. 42, no. 2, pp. 17-27, Apr. 2000.
27. T. J. Cui, W. C. Chew, A. A. Aydiner, D. L. Wright, D. V. Smith, and J. D. Abraham, "An Addendum to 'Numerical modeling of an enhanced very early time electromagnetic (VETEM) prototype system'," *IEEE Antennas and Propagation Magazine*, vol. 42, no. 3, pp. 54-57, June 2000.
28. T. J. Cui, W. C. Chew, A. A. Aydiner, D. L. Wright, D. V. Smith, and J. D. Abraham, "Detection of buried targets using a new enhanced very early time electromagnetic (VETEM) prototype system," *IEEE Trans. on Geoscience and Remote Sensing*, to be published.
29. T. J. Cui and W. C. Chew, "Fast evaluation of Sommerfeld integrals for EM scattering and radiation by three-dimensional buried objects," *IEEE Trans. on Geoscience and Remote Sensing*, vol. GE-37, pp.887-900, Mar. 1999.
30. T. J. Cui and W. C. Chew, "Efficient method for the near-field detection of buried dielectric and conducting objects," *Electromagnetics*, vol. 18, pp. 555-573, no.6, 1998.
31. T. J. Cui and W. C. Chew, "Fast algorithm for electromagnetic scattering by buried conducting plates of large size," *IEEE Trans. on Antennas and Propagation*, vol. 47, pp. 1116-1118, Jun. 1999.
32. T. J. Cui and W. C. Chew, "Fast algorithm for electromagnetic scattering by buried 3D dielectric objects of large size," *IEEE Trans. on Geoscience and Remote Sensing*, vol. GE-37, pp. 2597-2608, Sep. 1999.

33. J. M. Song and W. C. Chew, "Fast multipole method solution using parametric geometry," *Microwave Opt. Tech. Lett.*, vol. 9, no.16, pp. 760-765, Nov. 1994.
34. T. J. Cui, W. C. Chew, A. A. Aydinler and S. Y. Chen, "Inverse scattering of 2D dielectric objects buried in a lossy earth using the distorted Born iterative method," *IEEE Trans. on Geoscience and Remote Sensing*, vol. 39, no.1, Jan. 2001 (in press).
35. T. J. Cui and W. C. Chew, "Frequency-spatial domain inverse scattering of two-dimensional dielectric objects buried under a lossy earth," Research Report, Electromagnetics Laboratory, University of Illinois at Urbana-Champaign, No. CCEM-19-99, July 1999.
36. T. J. Cui and W. C. Chew, "Novel diffraction tomographic algorithm for imaging two-dimensional targets buried under a lossy earth," *IEEE Trans. on Geoscience and Remote Sensing*, vol. 38, pp. 2033-2041, no. 4, Part 2, July 2000.
37. T. J. Cui and W. C. Chew, "Diffraction tomographic algorithms for the detection of three-dimensional objects buried in a lossy half space," Research Report, Electromagnetics Laboratory, University of Illinois at Urbana-Champaign, No. CCEM-6-00, February 2000.
38. A. A. Aydinler, W. C. Chew, T. J. Cui, D. L. Wright, D. V. Smith, and J. D. Abraham, "3D imaging of large scale buried structure by 1D inversion of very early time electromagnetic (VETEM) data," *IEEE Trans. on Geoscience and Remote Sensing*, vol. 39, no.4, July 2001 (in press).
39. T. B. Hansen and P. M. Johansen, "Inversion scheme for monostatic ground penetrating radar that takes into account the planar air-soil interface," *IEEE Trans. on Geoscience and Remote Sensing*, vol. GE-38, pp. 496-506, Jan. 2000.
40. Wright, D.L., Smith, D.V., Abraham, J.D., Smith, R.T., Cui, T.J., and Chew, W.C., 1999, New field and modeling results from a simulated waste pit using the enhanced very early time electromagnetic (VETEM) prototype system: Proceedings of the Symposium on the Application of Geophysics to Engineering and Environmental Problems, Oakland, CA, March 14-18, 1999, p. 811-820.
41. Abraham, J.D., D.V. Smith, and D.L. Wright, 2001 (*in press*), A survey of waste pits at the Idaho National Engineering and Environmental Laboratory using the new USGS prototype ATV towed VETEM platform: Proceedings of the Symposium on the Application of Geophysics to Engineering and Environmental Problems (SAGEEP), 2001, March 4-7, 2001, Denver, CO.

42. Wright, D.L., Smith, D.V., and Abraham, J.D., 2000a, A VETEM survey of a former munitions foundry site at the Denver Federal Center: Proceedings of the Symposium on the Application of Geophysics to Engineering and Environmental Problems, Arlington, VA, February 20-24, 2000, p. 459-468.
43. Wright, D.L., and Chew, W.C., 2000, Advanced subsurface imaging with applications to buried structures, waste pits, and characterization of the vadose zone, a Joint Proposal submitted to the U.S. Department of Energy, Office of Science, Environmental Management Science Program by the U.S. Geological Survey and the University of Illinois at Urbana-Champaign, 31 p. plus attachments.