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Project Title: **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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NEW FIELD AND MODELING RESULTS FROM A SIMULATED WASTE PIT USING THE ENHANCED VERY EARLY TIME ELECTROMAGNETIC (VETEM) PROTOTYPE SYSTEM

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ABSTRACT

Tests in July, 1998, of an improved version of the prototype VETEM system demonstrated improved depth of investigation at the Cold Test Pit (CTP) at the Idaho National Environmental and Engineering Laboratory (INEEL). The improved depth of investigation is due primarily to the development of larger loop antennas and a new transmitter capable of driving up to 30 times more current than the original transmitter into the larger loop. An overlapped antenna configuration was tried and proved effective in detecting buried objects. New display software allows us, for the first time, to generate areal time-slice displays of our data in the field for fast qualitative evaluation. Comparisons of results using two different antenna configurations over the Large Object Pit portion of the CTP show generally good agreement, but show an apparent position offset of the two data sets from each other. The test over the Calibration Cell portion of the CTP using the overlapped antenna configuration successfully located most of the indicated targets in the cell. Results over both portions of the CTP suggest that the indicated locations of some of the buried objects may not be completely accurate. New antenna and 3D forward modeling codes run using an input waveform, antenna size and configuration, and system bandwidth matching those of the VETEM system produce waveforms and show sensitivities similar to those seen in recorded field data.

INTRODUCTION

Delineation and characterization of buried waste pits is a matter of concern for the U.S. Department of Energy (DOE) and other agencies. A simulated waste pit, the CTP, was constructed at the INEEL (Figure 1). Although none of the buried objects in the pit are radioactive, the other characteristics of the buried objects were chosen to be representative of actual buried waste pits at the INEEL. Some of the buried objects are electrically conducting and ferromagnetic, whereas others, of cardboard and wood, for example, are not. The objects buried in the CTP also vary in size, shape, and depth, and may have been put in place by stacking or by random dumping with consequent random orientations. Numerous electromagnetic (EM) systems, VETEM among them, were tested at the CTP, as part of the Electromagnetics Integrated Demonstration, in 1995. The 1995 VETEM test results were encouraging, but indicated some needed improvements which we are currently pursuing.

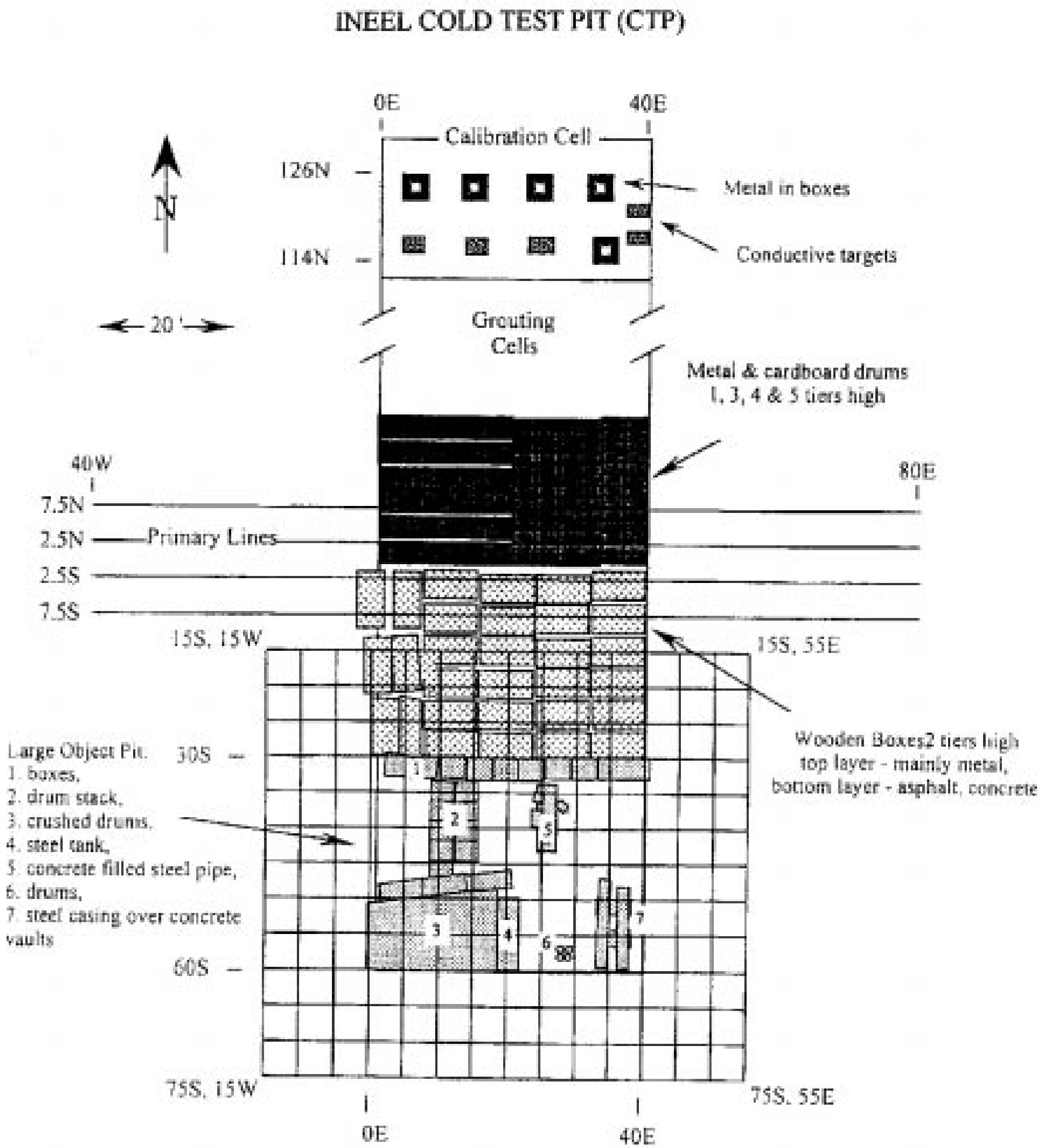


Figure 1. Map of the Cold Test Pit, Idaho National Environmental and Engineering Laboratory.

VETEM was conceived to fill a gap between ground penetrating radar (GPR) systems that operate in the tens or hundreds of MHz range, and time domain electromagnetic (TDEM) systems that typically operate in the kHz to tens of kHz range. GPR frequently cannot penetrate to sufficient depths through electrically conductive clay caps that often cover waste pits. TDEM systems have better depth of penetration, but suffer from poor resolution, especially in the first five meters of depth. The design goals of the VETEM system include better penetration through conductive media than GPR, and better shallow resolution than current TDEM systems.

MODIFICATIONS TO THE VETEM SYSTEM

Tests of the earlier prototype version of VETEM at the CTP in 1995 were very encouraging, but also pointed to some modifications that might improve the performance of the system (Wright and others, 1996). Since 1995 the following changes have been made to the VETEM system:

- a longer and more rigid nonmetallic platform to allow greater antenna spacing with less flexing (Figure 2),
- new square loop antennas with 10 times the area of the original antennas (Figures 2 and 3),
- a new longer-pulse transmitter capable of driving up to 30 times more current through the transmitting loop,
- a new shorter-pulse transmitter suitable for small loops and perhaps electric field antennas,
- a new digitizer/stacker unit integrated into the data acquisition PC,
- an onboard global positioning system (GPS) for supplementary position information, and
- image processing software to generate areal time-slice displays of the VETEM data.

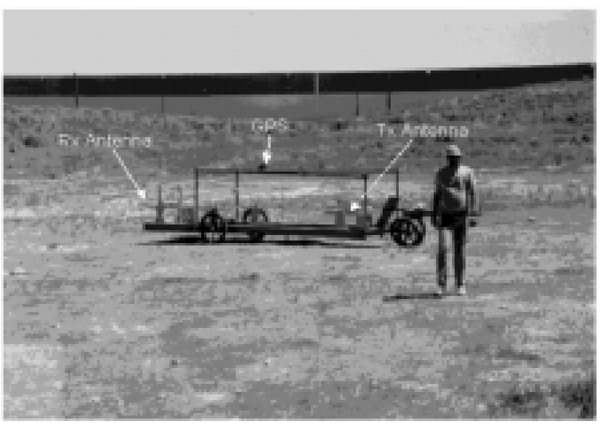


Figure 2. New platform, antennas, and GPS.

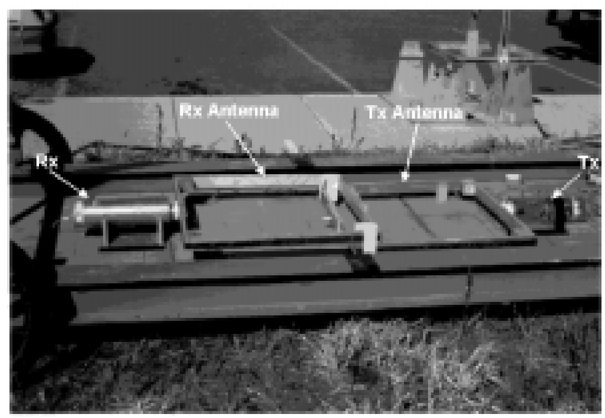


Figure 3. Overlapped antenna configuration.

EXPERIMENTS AT THE CTP

Procedure

In July of 1998, we revisited the CTP with the modified VETEM system. A large number of lines that had been done in 1995 were repeated, mainly with the new larger antennas. Several configurations were used with these antennas:

- 4-meter spaced co-planar and perpendicular antennas,
- 2-meter spaced perpendicular antennas, and
- overlapped antennas, adjusted to minimize the sum of the primary field and secondary earth response.

The 4-meter antenna spacing was tested to determine whether it gave improved response to deep targets. We show no 4-meter spaced results in this paper, because at 4-meter separation spatial resolution suffered, and because the 2-meter spaced perpendicular and the overlapped antennas appear to have provided adequate depth of penetration. The overlapped antenna configuration, shown in Figure 3, was tried for the first time in 1998, and proved to be effective for the detection of discrete buried objects.

Results at the Large Object Pit (LOP)

We show data acquired with 2-meter spaced perpendicular antennas and with overlapped antennas. For each transmitted pulse a complete received waveform was digitized, consisting of 8192 samples at 2 nanoseconds per sample. Each recorded waveform was obtained by averaging 4096 received waveforms. The spatial data density along each line was approximately 12 cm. The lines were run from east to west at a line spacing of 1.524 m (5 feet) to conform to the existing grid lines. A 1-m line spacing might have provided slightly better results. Figure 4 shows results over the LOP portion of the CTP with buried targets crosshatched and labeled according to the key given in Figure 1. Figure 4A shows the results with 2-meter spaced perpendicular antennas, and 4B shows the results with overlapped antennas. In each case the plotted location is referenced to the midpoint between the receiving and transmitting antennas.

The area from 0E to 40E and north of -30N contains wooden boxes filled with metal and nonmetallic materials. The area labeled " 1 " is an area of unspecified boxes, "2" is a drum stack, "3" is crushed drums, "4" is a steel tank, "5" is a concrete-filled steel pipe, "6" is drums of unspecified type, and "7" is steel casings over concrete vaults.

Figure 4 is derived from "residual" data. Residual data are calculated along each line by calculating the average received waveform for that line and subtracting it from each individual waveform along the line. Because the data are irregular over the site (dense along a survey line, sparse between lines), the data were gridded and smoothed with a two-dimensional boxcar filter to produce color graphical displays. The VETEM antennas are configured such that areas with positive residual values during the transmitter "on" time and negative residual values at late times after the transmitter is turned off indicate areas of relatively higher electrical conductivity. Highly conductive areas are assigned "hotter" colors (reds and yellows), whereas less conductive areas are represented by the cooler colors (blues and purples). Color bars annotate how the amplitudes, in digitizer units, are scaled. The digitizer units can be converted to receiver loop current once the receiver has been fully calibrated. The color scales have been stretched to produce visually similar results.

We see a response from the wooden box forms in the north-central region of the data, roughly centered at 27E in Figure 4A and 25E in Figure 4B. No response from "1" can be unambiguously identified. The response from "2" is clear in both Figures 4A and 4B, but the data suggest that the location of "2" may not be accurately represented in the site plan (Figure 1 and overlays). Indeed, another map of the site shows the locations of items "2", "3", "4", and "6" shifted 2.7 feet to the west relative to the locations shown. If the peak response to "2" were placed at the center of "2" a shift of approximately 5 feet to the west would be required. It is not clear whether object "4", a steel tank, can be distinguished from the immediately adjacent crushed drums, object "3", although the strong conductive anomaly at approximately 17E, -53N in Figure 4A might be due to the steel tank, if the actual location of the tank is about 4 or 5 feet to the west of that indicated in the plan map. Whether or not the steel tank can be distinguished

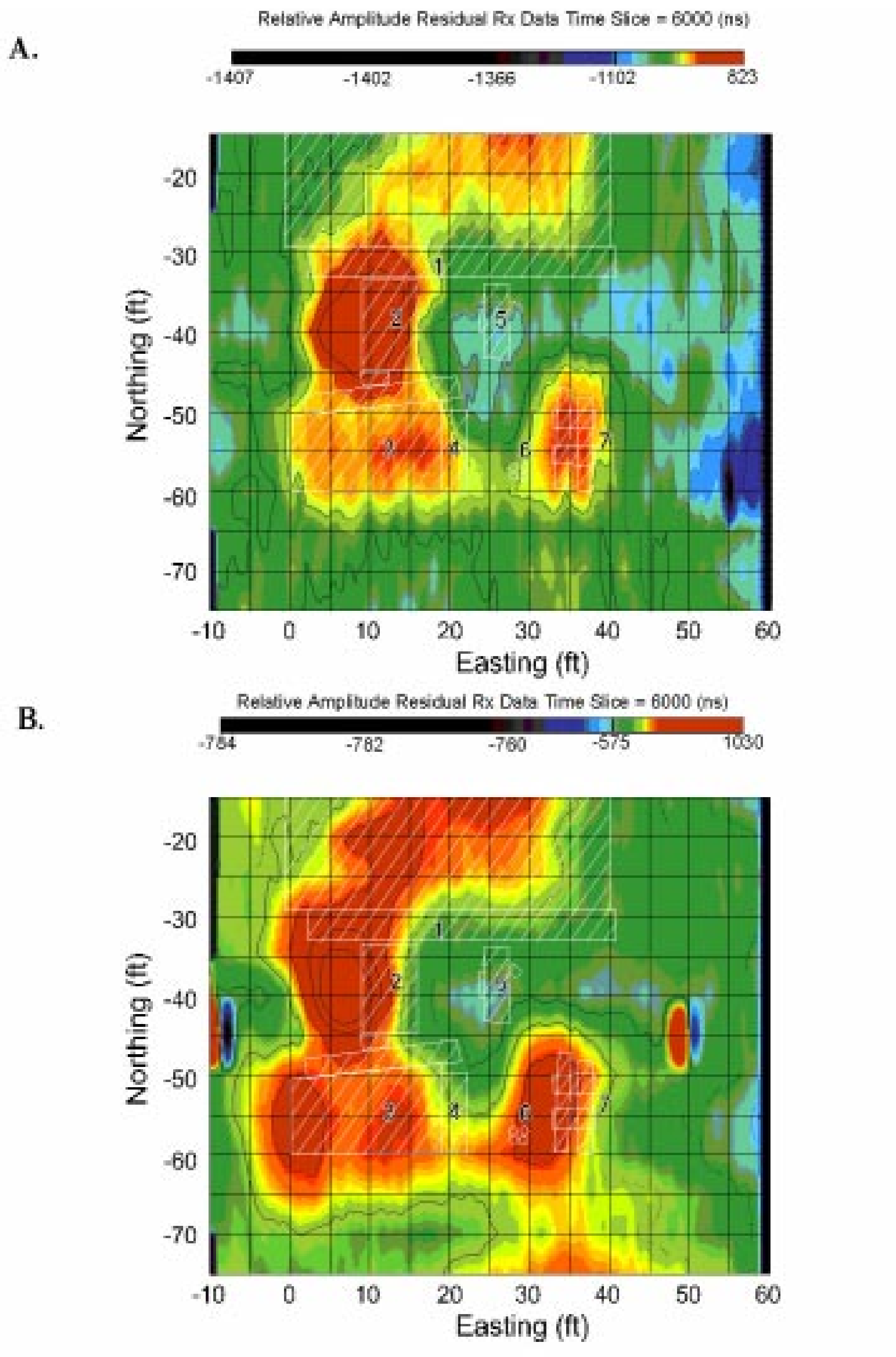


Figure 4. VETEM residual data with target map overlay. A. Perpendicular antennas B. Overlapped antennas

from the crushed drums, the drums, item "3", correspond to the broad yellow and orange area between -50N and -60N from 0E to 15E or 20E in Figure 4A, and to the elevated conductivity zone in the same area of Figure 4B. We see no feature corresponding to "5". No clear response from "6" can be discerned. Though "7" shows up clearly, the two separate steel casings do not show distinctly in the smoothed images, though there is a suggestion of two objects in Figure 4A. In the raw unsmoothed data the two casings appear to be resolved.

As a general observation, we note that the perpendicular antenna configuration data in 4A appears to be shifted by about 2 or 3 feet farther east as compared to the overlapped antenna configuration data of 4B. Although the overlapped antennas would seem better able to provide accurate target registration, the perpendicular antenna data agree better with the mapped positions of buried objects, particularly "7". The 2-D interpolation that was applied to produce Figures 4A and 4B stretches the responses in the vertical (north-south) direction. This is a consequence of the fact that the data density is about 12 times higher along the lines than from line-to-line.

The overlapped antenna configuration provides much stronger response to very shallow buried objects. For example, at 50E, -45N we found an undocumented piece of metal pipe partially exposed at the surface. A strong response is seen in 4B, but only a very low amplitude response is apparent in 4A. The relative advantages of overlapped versus perpendicular antenna configurations may ultimately be better understood using comparative forward modeling.

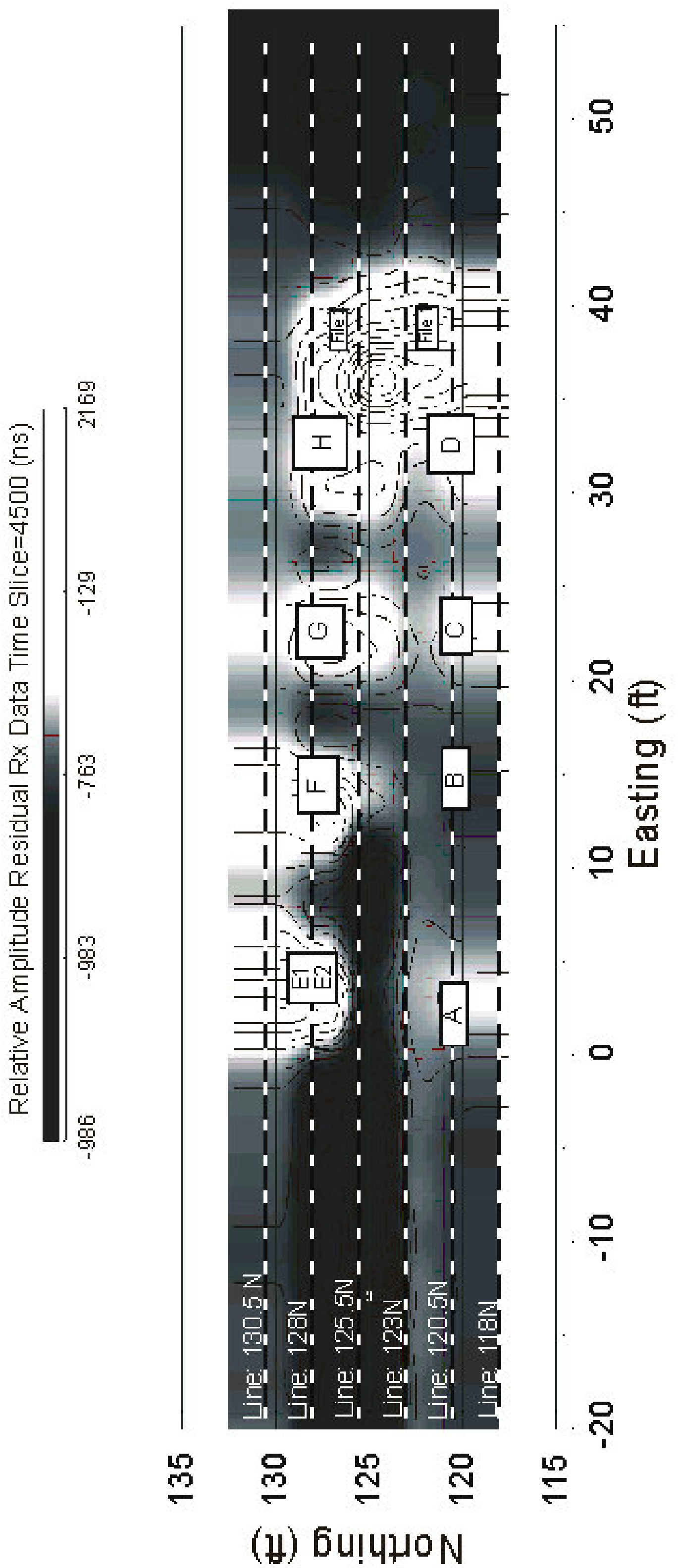
Results at the Calibration Cell

Figure 5 shows data at time slice 4500 nanoseconds over the Calibration Cell portion of the CTP using the overlapped antennas and a line spacing of 2.5 feet. Locations and symbols for buried objects have been superimposed on the image. As in Figure 4 the data are presented in digitizer units as the waveform residual. The system recorded strong responses to all the targets, except for "B", which also was undetected in previous EM surveys (Zonge, 1998; Rust Geotech, 1996). Most conductivity signatures are shifted slightly west from the documented locations, either because of antenna configuration or positional inaccuracies. Note that the anomalies are not aligned with the target map. The skew of targets with respect to the site grid also appears in the results of previous surveys (Zonge, 1998; Rust Geotech, 1996), and probably results from inaccurate documentation of the placement of the objects at the time of burial.

NUMERICAL MODELING

Numerical modeling of the VETEM system includes new antenna modeling code and code for 3D scattering from buried objects. The foundations for the methods of numerical modeling described below can be found in texts such as Chew, 1995 and Harrington, 1968.

For arbitrarily-shaped and arbitrarily-oriented wire antennas above or buried in lossy ground, we developed a new accurate model using Galerkin's method. Generally there are three limitations in antenna modeling. First, the current is assumed to flow on the axis of the wire and testing is performed on the surface, or the current is on the surface and testing is along the axis. Second,



Item ID	Waste form type	Dimensions	Contents
A	Drum w/liner (55 gal)	24 in. dia. x 36 in.	Concrete
B	Plastic drum (30 gal)	18 in. dia. X 29 in.	Salt water
C	Drum w/liner (55 gal)	24 in. dia. x 36 in.	Foam
D	Wood box	2 x 4 x 4 ft.	Wood and Paper
E	Wood boxes (2, stacked)	2 x 4 x 4 ft. (each)	E1=Wood and Paper E2=Ferrous metals
F	Wood box	2 x 4 x 4 ft.	Mixed metals
G	Wood box	2 x 4 x 4 ft.	Nonferrous metals
H	Wood box	2 x 4 x 4 ft.	Dense-pack metal
File 1	Five-drawer metal file cabinet	14 x 28 x 57 in.	Empty
File 2	Five-drawer metal file cabinet	14 x 28 x 57 in.	Empty

* Based on EG&G Idaho, Inc. FORM EGG-2631/(Rev. 01-92)

Figure 5. VETEM residual data over the calibration cell using overlapped antennas.

the delta gap is adopted as the source model for most wire antennas. Finally, the input admittance of the wire is simply defined as the ratio of current to voltage at the driving point.

In this model, however, we assume that the current is flowing on the surface and the testing is also performed on the surface. To replace the delta-gap source, a more accurate source model is developed by using Huygens' principle. From this principle and the reciprocity theorem, a variational formulation of the input admittance is derived in a general form.

Under the assumption that the current is only a function of arc length along the wire, the dyadic Green's functions in this model can be simplified by using directional derivatives. The resulting impedance matrix and source vector contain the contributions of the primary field in a homogeneous space and the reflected field from the half space, the latter represented by Sommerfeld integrals. For the primary-field term, closed-form formulations have been obtained for both the self term and the mutual term of the impedance matrix and source vector by using Taylor's expansion. Therefore, the computational time of the accurate model is equivalent to that of the older models.

In order to handle large buried objects, we developed a 3D-scattering code using the conjugate gradient (CG) method and the fast Fourier transform (FFT). This code contains two fast algorithms for EM scattering by buried conducting plates and buried dielectric objects.

In the fast algorithm for buried conducting plates, Galerkin's method is first applied to discretize the electric-field integral equation, in which roof-top functions are chosen as both basis and testing functions. Then the CG-FFT method is used to solve the resulting discrete linear system. The near scattered field in the upper region can also be evaluated by the FFT algorithm. Due to the use of the FFF in handling the cyclic convolutions related to Toeplitz matrices, evaluation of the Sommerfeld integrals for buried scatterers, 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 MNlogN, where M is the number of iterations and M<<N for large problems.

In the fast algorithm for buried dielectric objects, methods similar to those for conducting plates have been used. However, both cyclic convolution and correlation terms are involved in the resulting matrix equation. The cyclic correlation can also be rapidly evaluated using the FFT.

As a computational example, consider the VETEM 30-inch square transmitting and receiving loops spaced 2 m apart, with the transmitting loop parallel and the receiving loop perpendicular to the ground and both loops 21 inches above the ground, which is assumed to have a relative dielectric permittivity of 10. In the numerical modeling, the transmitter and receiver can be regarded as a whole system. When the driving signal is a double ramp with a rise time of 2000 ns to a normalized peak of 1 A and a fall time of 100 ns, as shown in Figure 6, the current on the shorted receiving loop is illustrated in Figure 7 for different earth conductivities.

When a 2 m by 2 m conducting plate is buried in the ground, the total induced current on the receiving loop is shown in Figure 8 for burial depths of 0.5 m and 1.0 m when the earth conductivity is 0.05 S/m and the relative dielectric permittivity is 10. Figure 8 illustrates the receiver current sensitivity to shallow buried objects. Further calculations of this kind will enable us to determine the expected shape and magnitude of responses to various buried objects and to changes in earth electrical parameters for various antenna configurations and polarizations. From these calculations compared to system noise measurements we can also estimate detection limits for the VETEM system.

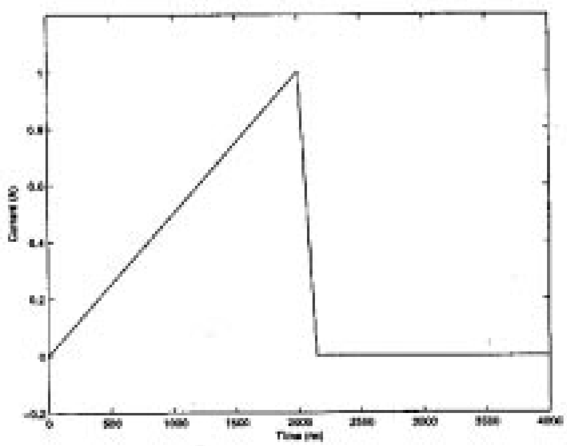


Figure 6. The normalized transmitting loop current.

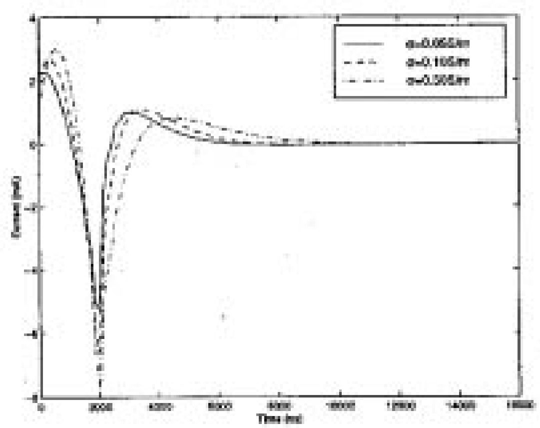


Figure 7. Sensitivity to earth conductivity.

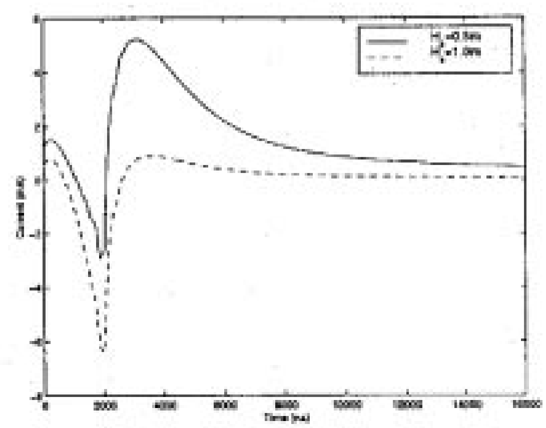


Figure 8. Sensitivity to plate burial depth.

CONCLUSIONS AND CONTINUED DEVELOPMENTS

Enhancements to the VETEM system have increased the sensitivity and reduced system noise. In addition, we can now produce time-slice maps in the field for rapid reconnaissance and improved detection of buried waste forms. An initial qualitative analysis of minimally processed data has yielded high-resolution images of conductivity anomalies corresponding closely to mapped target locations. More sophisticated smoothing and image processing algorithms are expected to improve image definition. A more intensive, quantitative treatment of the data is pending, using forward and inverse modeling to derive estimates of target depth and physical parameters, such as size and composition. Complementing the continued hardware development at the USGS, the Department of Electrical and Computer Engineering at the University of Illinois, Urbana-Champaign, has developed new antenna and 3D forward modeling algorithms appropriate to the VETEM system parameters and buried objects similar to those at the CTP

(Wright, et al., 1998). In addition, the University of Illinois has initiated work on a fast, approximate, 1D inverse solution to be run on a PC in the field.

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