Project 86992
Improving Ground Penetrating Radar Imaging in High Loss Environments by Coordinated System Development, Data Processing, Numerical Modeling, & Visualization

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RESULTS TO DATE: Improving Ground Penetrating Radar Imaging in High Loss Environments by Coordinated System Development, Data Processing, Numerical Modeling, and Visualization Methods with Applications to Site Characterization EMSP Project 86992 Progress Report as of 9/2004.

1. Research Objective: The Department of Energy has identified the location and characterization of subsurface contaminants and the characterization of the subsurface as a priority need. Many DOE facilities are in need of subsurface imaging in the vadose and saturated zones. This includes 1) the detection and characterization of metal and concrete structures, 2) the characterization of waste pits (for both contents and integrity) and 3) mapping the complex geological/hydrological framework of the vadose and saturated zones. The DOE has identified ground penetrating radar (GPR) as a method that can non-invasively map transportation pathways and vadose zone heterogeneity. An advanced GPR system and advanced subsurface modeling, processing, imaging, and inversion techniques can be directly applied to several DOE science needs in more than one focus area and at many sites. Needs for enhanced subsurface imaging have been identified at Hanford, INEEL, SRS, ORNL, LLNL, SNL, LANL, and many other sites. In fact, needs for better subsurface imaging probably exist at all DOE sites. However, GPR performance is often inadequate due to increased attenuation and dispersion when soil conductivities are high.

Our objective is to extend the limits of performance of GPR by improvements to both hardware and numerical computation. The key features include 1) greater dynamic range through real time digitizing, receiver gain improvements, and high output pulser, 2) recording the direct arrival at the receiving antenna, supplemented with additional sensors if necessary, to allow dynamic determination of the radiated waveform, 3) modified deconvolution and depth migration algorithms exploiting the new antenna output information, 4) increased ability to perform automatic full waveform inversion made possible by the known radiated pulse shape.

2. Research Progress and Implications: This report summarizes progress after 24 months of a 3 year project.

Electronics - A critical element in the research is to extend the effective depth of investigation by increasing the dynamic range of GPR by means of electronics improvements and real time waveform averaging. The progress we have made on this element includes:

a. Identification and procurement of the most suitable, highest performance, waveform digitizer/averager. We selected and have procured two Acqiris model AP-200 units. These units allow us to digitize and average waveforms in real time with no equivalent-time sampling needed. This yields a substantial improvement in signal-to-noise ratio by real-time waveform averaging. One unit is intended for recording the received waveform. The second can be used as a backup or to record data from auxiliary sensors to determine the pulse radiated into the earth to assist waveform inversion. A change from our previous path is that FDTD simulations show that current sensors in the transmitting antenna will not be an adequate measure of the radiated waveform, so we do not plan to embed these along the length of the antennas.

b. LabView data acquisition software has been written for the AP-200. This software also includes a provision for including differential global positioning system data in the data stream. This provision is important because accurate positions are crucial to high quality GPR subsurface images, particularly 3D images.

c. Two alternative methods of electronic receiver dynamic range extension have been investigated: 1) Real-time gain ramping to preferentially boost the amplification of later (smaller) signals relative to the earlier (larger) signals, and 2) Linear/logarithmic amplification that linearly amplifies small signals, but progressively decreases the gain for larger signals. Both of these approaches show promise, but we have selected the linear/logarithmic amplifier because it does not require active control. The linear/logarithmic receiver is complete except for mounting hardware.

d. Pulser designs have been examined including ones designed at the USGS. Although it may be that we will require a combination of designs to provide a range of outputs matched to various antennas, we have procured a high output unit from a commercial vendor. Because of certain operating constraints of this pulser we have not been able to accurately characterize the pulser as a stand-alone unit. We will have to characterize it in combination with transmitting antennas which have been designed and are under construction. We have tested the new pulser with a prototype linear dipole antenna and measured a pulse rise time of 3 ns and amplitude of 6 kV. We need the pulser output for our numerical antenna and radiated waveform simulations

Antenna Design Simulation - A second critical element is antenna design. We have numerically simulated the radiated waveforms from linear dipoles and resistively loaded linear dipoles and bowtie antennas with and without back shields and with a variety of driving pulse shapes and a range of soil conductivities. These simulations, conducted using a finite difference time domain (FDTD) program, have guided our antenna designs. Ground coupled GPR antennas are sensitive to conditions near the antenna, although resistive loading on the antennas reduces this sensitivity. FDTD simulations have been made to investigate the effects of antenna near zone conditions on the transmitted waveform. Relevant near zone parameters include earth permittivity and conductivity and height above the ground. Each of these parameters changes the shape and directional radiation pattern of the transmitted waveform. The goal is to predict the transmitted waveform shape using information from simulations, experimental measurements and sensors to monitor the waveform in real time. FDTD simulations show only weak dependence of the transmitting antenna current on changes in antenna position and earth properties. Therefore the original idea of monitoring current transients along the antenna to predict the shape of the transmitted waveform will not be continued. If the transmitting antenna current is monitored, it will only be at the antenna driving point to monitor pulser output. We have concluded that we will use linear dipoles with resistive loading to shape our output pulse. The fixed antenna resistive loading, transmitter input pulse shape, back shield, and variable earth loading combine to determine the radiated pulse shape.

We have also defined the shape and size for our back shield. This shield is needed to minimize undesirable radiation into the air, but its presence influences the radiated waveform. The back shields are fabricated. Formerly, we had assumed that internal RF loading materials would sufficiently damp internal reflections that the back shield would have only a minor effect on the radiated waveform. Some available RF materials had a relatively high dielectric permittivity, however, with the consequence that too much of the energy would be directed into the RF material and away from the ground where it must go to be useful. We may leave the shield unloaded and compensate for the resulting additional radiated waveform-ringing-numerically by simply including this in the deconvolution. We may also implement alternative RF absorbing materials that do not have a high dielectric permittivity. The earth loading effects of permutations of the variable operating parameters (permittivity, conductivity, and standoff) are complicated. A goal of the simulations was to determine whether the transmitted wave shape could be uniquely determined by monitoring the antenna operation; and if so, what type of sensors would be needed. The results show that permittivity and conductivity can probably be determined with reasonable sensitivity by monitoring the electric field near the antenna. Changes in permittivity produce both variable delays in the direct waves and changes in amplitude. Variation in conductivity causes changes in amplitude. Antenna standoff above the ground also affects the transmitted waveform. The standoff causes particularly large effects on the transmitted waveform and the sensed electric field near the antenna. This problem will be minimized if the standoff is determined by other means. We have tentatively concluded that it may be possible to use early signals from the receiving antenna to estimate the shape of the transmitted waveform.

This information has generally been treated as noise and largely ignored in GPR surveys. Acoustic distance measuring sensors to determine standoff will be added if experiments show that we need them.

GPR Processing Algorithms - The two primary data processing steps that need to be specialized for improved interpretability of GPR data are deconvolution and migration. Our work on both of these steps is tied to our hardware developments. If we probe the earth with a simple, single spike pulse of energy, then any reflected return signatures that are not simple spike shapes tell us something about the earth. Unfortunately, real GPR systems probe the earth with a pulse shape that is usually not simple. Furthermore, the pulse shape changes as the properties of the earth near the antenna change. This makes it difficult when looking at GPR data to separate the earth effects from the changing pulse shapes of the system. At its best, deconvolution is a process that uses an understanding of the changing pulse shape of the system, and everywhere in the data converts the pulse into a simple, single spike. Two types of deconvolution are common. Deterministic deconvolution is applied when the possibly complicated pulse shape is known through independent measurements. With the desired shape known (usually a simple spike), and the input pulse shape known, one simply creates a routine to search the data and everywhere convert the input pulse into the desired pulse. If the pulse shape is not known, adaptive deconvolution must be used. In this case statistical information from the data is combined with assumptions to estimate what the system pulse shape was at any location. This can work well when the assumptions about the system are correct. For example, when explosives are used to acquire seismic data, it is possible to make assumptions that always hold for the pulse shape entering the earth as a result of an explosion. For GPR data, broad, useful assumptions are clearly not the same as for seismic data, and have not yet been successfully identified. Assumptions that may work on data collected with a given system in a given location, may not work at all with another system or in another location.

Our progress on deconvolution is expected to occur mainly in the later stages of our research effort, once our system hardware is built. Through computer modeling we are examining the effects various system designs have on the pulse shape, and our ability to identify the pulse shape from our system as it is used in different environments. We desire built in aspects of our system that will help us to understand its output pulse shape at all times. This will allow us to use deterministic deconvolution to improve our data. In the event we must use adaptive deconvolution, we need a thorough understanding of our system response in all conditions to best design the assumptions to be used in a new algorithm.

Our goal with migration improvements is to account for the dispersive nature of GPR propagation through conductive earth materials. To date, we are completing a modification of a standard frequency-wavenumber migration program to account for velocity variances with frequency. We use a Cole-Cole dispersion model to describe how velocity varies with frequency, and account for this variance as the data are moved laterally and summed. A limitation in our current algorithm is that it can only account for one constant dispersive medium. Once we prove that it is effective for this case, we will work on modifications to extend the dispersive correction to variable media. It is clear from our work to date on dispersive migration that to be most useful it requires data with high signal quality. The dispersive characteristics of the data that we are correcting for are subtle enough to be unresolvable in common GPR data. This is because dispersion is always accompanied by high attenuation, such that only a system with high signal-to-noise characteristics can record dispersive effects.

In summary, our progress on processing algorithms has been steady and careful. We want our new processing tools to work with our new system such that the combined package will result in more interpretable GPR data. We have written and presented a paper on a dispersive f-k migration program (see Section 4, below).

3. Planned Activities:

Because sensing currents along a ground-coupled antenna is inadequate to predict the radiated waveform, we plan to continue our antenna modeling studies to determine a useful combination of near-field electric field sensors and perhaps acoustic standoff and orientation sensors, if needed, build physical antennas incorporating these sensors and implement a system using these antennas, our new receiver design, and new pulser. We will then carry out some physical modeling of our antennas and systems to verify our FDTD numerical simulations. The final phase of FDTD modeling will be to conduct extensive forward modeling, and the results used to calculate the transmitted wave shapes for our antennas as a function of the near field antenna parameters. The computationally time consuming parts of the forward model will be made in advance for the typical range of the near field parameters. A library of forward modeled wave shapes will be compiled. This library can then be used to quickly find the transmitted waveforms, which then provide a basis for deconvolution and migration of a GPR data set. Each library entry contains the information to quickly calculate the waveforms in the subsurface. The appropriate library entry will be selected by comparing early signals at the receiving antenna with the simulated results in the library. The entire operation of determining the transmitted waveform and then deconvolving and migrating a radar data set could be done in minutes. The result is expected to be a significant enhancement of the images presented to operators in the field.

We plan to integrate essential hardware and data acquisition components into a field worthy prototype system by approximately October, 2004 which is later than our original estimate of June, 2004. We are in the midst of building the hardware and some delays have been encountered. Additional refinements to the system are expected to continue for the duration of this research. When a working prototype is available we will look for applications at DOE sites.

In parallel with the development of the system we will continue work on the development of an automatic inversion to better estimate the properties of unknown layers by taking advantage of better knowledge of the actual radiated waveform from recorded transmitting antenna data. Should deterministic deconvolution and migration prove intractable, we will develop adaptive algorithms.

4. Information Access:

1. http://www.pnl.gov/emsp/fy2003/presentations/wright_david_86992.pdf.

2. Powers, M.H., and Oden, C.P., 2004, Migration of dispersive GPR data: Proceedings of the Tenth International Conference on Ground Penetrating Radar, Delft, The Netherlands, June 21-24, 2004, p. 333-336.

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