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

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EMSP Project 86992 Progress Report as of 12/2003

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) modified, fully characterized antennas with sensors to allow dynamic determination of the changing radiated waveform, 3) modified deconvolution and depth migration algorithms exploiting the new antenna output information, 4) development of automatic full waveform inversion made possible by the known radiated pulse shape.

Research Progress and Implications

This report summarizes progress after 16 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 and the second is intended to record data from transmitting antenna sensors to determine the pulse radiated into the earth to assist in waveform inversion. 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. 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 and we are presently characterizing that pulser so that its output can be used in our numerical antenna 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, will guide our antenna designs. Ground coupled GPR antennas are sensitive to conditions near the antenna. 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, height above the ground, and the orientation angle of the antenna with respect to 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 sensors added to monitor the antenna conditions in real time. FDTD simulations show only weak dependence of 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. The effects of all permutations of the four operating parameters (permittivity, conductivity, standoff, and angle) 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 can be determined with reasonable sensitivity by monitoring the electric field near the antenna. The sensitivity for conductivity is much lower. It is possible that conductivity could be predicted from the electric field data as well, but with less certainty. Antenna standoff above the ground and the angle the antenna makes with the ground also affect the transmitted waveform. The standoff causes particularly large effects on the transmitted waveform and the sensed electric field near the antenna. Since the sensitivity to conductivity is small, combinations of other parameters will easily mask the effects of conductivity. This problem will be minimized if the standoff and angle are determined by other means. We have concluded that we should monitor antenna operation from sensors measuring electric properties to determine the electrical properties of the earth, and from spatial sensors to determine antenna standoff and angle. The current plan is to add acoustic distance measuring sensors to the antenna to determine standoff and angle. The combination of electric field sensors with the acoustic sensors should allow all four near zone parameters to be estimated. We plan to build an antenna system that incorporates electric field monitors and acoustic distance measuring devices. The optimum positions of the electric field sensors near the antenna have not been determined. It is likely that the sensitivity to the four near field antenna parameters (permittivity, conductivity, standoff, and angle) could be increased by using multiple electric field sensors and/or optimizing the position of the sensors. Further modeling of antenna response will determine the spatial distribution of these sensors. In fact, 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. 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 that has been accurately deconvolved. 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 expect to have a journal paper submitted in the next month describing our initial dispersive f-k migration program.

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 acoustic standoff and orientation sensors, 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. 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 fieldworthy prototype system by approximately June, 2004, although 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: Further information on this project may be obtained from http://www.pnl.gov/emsp/fy2003/presentations/wright_david_86992.pdf.