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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

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3. RESEARCH OBJECTIVES

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, INL, 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 central objective was to extend the limits of performance of GPR by improvements to both hardware and numerical computation. The key features included 1) greater dynamic range through real time digitizing, receiver gain improvements, and high output pulser, 2) recording the direct arrival at the receiving antenna 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.

4. METHODS AND RESULTS

In order to achieve the goals of this research, progress both in GPR hardware and in data processing algorithms was required. We here provide brief summaries of accomplishments in these areas. For detailed information, we refer the reader to presentations, conference proceedings, papers and the Ph.D. thesis that were produced from this research project.

Electronics

A critical element in the research was 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 accomplishments on this element include:

a. Identification and procurement of the most suitable, highest performance, waveform digitizer/averager. We selected and 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 records 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.

b. LabView data acquisition software was 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 were 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 showed promise, but we selected the linear/logarithmic amplifier because it does not require active control. A linear/logarithmic receiver was built and incorporated into the system.

d. Pulser designs were examined. Two pulsers were used with the system.

In the course of field tests described below, we made refinements in the design of the radar system. The logarithmic amplifier implemented for range gain was optimized. Various transmission lines for control and the radar signal were improved. Additional circuitry to add a fiducial marker indicating the firing time of the pulse generator was required. This was because the time between sending a trigger pulse to the pulse generator and the firing time varies (presumably due to temperature).

Antennas

Both bowtie and dipole antennas were modeled using finite difference time domain (FDTD) code. Both dipoles and bowtie antennas were also physically tested and used with the system. The configuration used for the system calibration and characterization discussed below were circular cavity shielded dipoles. We procured radar absorbing foam and manufactured foam inserts for the dipole antennas. The antennas can be operated with or without the foam inserts. We found that the center frequency of these antennas without radar absorbing foam is about 80 MHz. Installing the foam inserts decreases this frequency to about 50 MHz, and results in a slightly more compact transmitted waveform. We also tested the system with a set of 75 MHz bowtie antennas.

System Calibration and Characterization

We made extensive measurements to characterize the response of the receiving electronics and the pulse generator. The receiving electronics were characterized with both time domain and frequency domain measurements. The response of the receiver electronics is a mild function of frequency, and the phase response is essentially flat. A special 200 ohm balanced transmission line was fabricated to facilitate these measurements.

Several methods were used to estimate the output of the pulse generator. The two that provided the best results were to 1) use a high frequency current probe, and 2) use a high voltage oscilloscope probe to carefully measure the output of the generator. This process is not straightforward at radar frequencies because the presence of most measurement devices and their cables add an unwanted load to the circuit that would not be seen at lower frequencies. We found that the output closely resembles an integrated Gaussian with a rise time of 2.5 ns.

The response of the antennas was modeled through FDTD simulations. The antenna response is affected by the electrical properties of the soil directly beneath the antennas. A physical description of these changes is quite complicated, but adequately treated by the simulation software. We have compiled a library of antenna simulations for various soil properties. This library is used in an inverse algorithm to determine soil properties as discussed below. With this library and the soil properties, the shape of the transmitted waveform can be determined. A large effort was made to maximize the accuracy of these simulations. The electrical properties of several antenna components were determined in a laboratory so that they could be properly specified for the simulations. The simulated response of the antennas was verified by comparison with experimental values. The response of the antenna array was measured in air and over water. Many updates to the simulated model were made to improve the simulated accuracy.

Custom signal processing software was written to extract the system response from experimental data. Using this software, the system response of essentially any GPR can be determined using standard electronics test equipment. The software provides the signal processing needed to compare the measured radar response to the simulated antenna response. It packages the system response so it can be used in the processing routines described below.

GPR Processing Algorithms

We developed algorithms to clarify subsurface images and better estimate the material properties of the reflectors. Since most GPR surveys are interpreted in the field without subsequent processing, these algorithms are designed to operate in near real time. The first algorithm estimates the soil properties under the bi-static antennas using a library of antenna response algorithms. The early waveforms at the receiving antenna change shape due to changing ground properties and height of the antennas above the ground. These changes are not simple monotonic changes in travel time or amplitude. However, a non-linear inversion can estimate the soil properties using the early time arrivals at the receiving antenna. These early time arrivals occur before subsurface reflections arrive at the antennas. Application of this algorithm is based on a quantitative assessment of the GPR system response.

The second algorithm clarifies subsurface images obtained in lossy (conductive) ground by reversing the dispersive effects of wave propagation. Using knowledge of the spectral content of the subsurface wave and the subsurface material properties, the algorithm effectively restores the portions of the wave field that have been attenuated by the lossy ground. The material properties are determined either from the first algorithm, from the hyperbolic move out and attenuation of scatterers, or by measuring soil samples in a laboratory. The algorithm also collapses diffracted waves by migrating the image while accounting for the frequency dependant velocity. The method performs well with noisy data, and may also clarify low frequency time domain EM images obtained from systems such as the VETEM and the EM61.

A third algorithm estimates the frequency dependant properties of a planar reflector using knowledge of the transmitted waveforms. This method is based on deterministic deconvolution. With a fully characterized radar system, the frequency dependant reflection coefficient of simple scatterers can be determined. Applications include determining the electrical properties of ground water at the water table. This might prove useful for mapping locations where saltwater is encroaching or where hydrocarbons are floating on the groundwater. This method could be extended to include cylindrical objects such as pipes.

Field Surveys

We have conducted surveys in several locations to test the performance of the radar and to refine the system. Repeated surveys have been conducted at the Denver Federal Center (DFC). The system was also deployed at the Colorado School of Mines Field Camp. Finally, we conducted surveys at three locations at INL. Data using the shielded dipole antennas were collected at all three sites. Data using the bowtie antenna was collected at the DFC and INL. Surveys using commercial radar equipment were also made at INL. The INL data were processed and delivered to INL personnel (Mr. Gail Heath) in an effort to assist a reactor deactivation and decommissioning operation.

5. RELEVANCE, IMPACT, AND TECHNOLOGY TRANSFER

GPR is one of the fastest and highest resolution geophysical tools available and when soil conditions permit its use it is almost unsurpassed in the ability to image and characterize the subsurface, hydrogeologic conditions controlling groundwater flow, and contaminant transport in the subsurface. In addition, GPR can often help in the assessment of the integrity of certain engineered barriers and other structures. However, high soil electrical conductivity due to salts and clay minerals in soil limits the effective depth of investigation. The prototype GPR developed in this research is intended to extend the depth of investigation in areas where the ground electrical conductivity is moderately higher than is generally considered the limit for GPR applications. In addition, we have developed methodology for measuring soil electrical properties in the near field of GPR antennas. This has value on its own merit for hydrogeology, but also for improving subsurface imaging in high loss and dispersive media. The impact of these improvements can be substantial at many DOE sites where subsurface characterization is important to understanding the controlling mechanisms for toxic material transport in the vadose zone, for example. Our means of technology transfer has been to present and publish our results, developments, and findings and interact with personnel at the national laboratories (See Sections 7 and 8). Our deployment to the INL assisted in reactor deactivation and decommissioning.

6. PERSONNEL SUPPORTED

Major research for this project was conducted by Mr. (now Dr.) Charles P. Oden at the USGS and the Colorado School of Mines. Dr. Oden completed his Ph.D. at CSM while working on this project at the USGS. His thesis and other publications completed or in process as products of this research are listed in Section 7.

In addition to Dr. Oden and the principal investigators, a strong contributor was Mr. Craig W. Moulton of the USGS who assisted with aspects of the GPR hardware and data acquisition software.

7. PUBLICATIONS

Wright, D. L., Oden, C. P., Powers, M. H., Moulton, C. W., Hutton, S. R., Kibler, J. D., Olhoeft, G. R., and Woodruff, W. F., 2005, A Ground Penetrating Radar System for High Loss Environments, *in* Proc. Symposium on the Application of Geophysics to Engineering and Environmental Problems, Atlanta, GA, p. 1-10.

Powers, M. H., and Oden, C. P., 2004, Migration of Dispersive GPR Data, *in* Proc. 10th International. Conference on Ground Penetrating Radar, Delft, The Netherlands, p. 333-336.

Oden, C. P., Wright, D. L., Powers, M. H., and Olhoeft, G. R., 2005, Ground Penetrating Radar Antenna System Analysis for Prediction of Earth Material Properties, *in* Proc. IEEE Antennas and Propagation Society International Symposium, Washington, DC, v. 3B, p. 76 - 79.

Oden, C. P., Wright, D. L., Powers, M. H., Olhoeft, G. R., Rittgers, J. B., Irons, T., and Meininger, A. J., 2006, Estimating Ground Properties under Ground-Coupled GPR Antennas, *in* Proc. 11th International Conference on Ground Penetrating Radar, Columbus Ohio, USA, paper AGR.3.

Oden, C. P., 2006, Calibration and Data Processing Techniques for Ground Penetrating Radar Systems with Applications in Dispersive Ground, PhD Dissertation, Dept. of Geophysics, Colorado School of Mines, Golden, CO, 249 p.

Oden, C. P., Powers, M. H., Wright, D. L., and Olhoeft, G. R., 2006, Improving GPR Image Resolution in Lossy Ground using Dispersive Migration, IEEE Trans. Geoscience and Remote Sensing, submitted.

Oden, C. P., Olhoeft, G. R., Wright, D. L. and Powers, M. H., 2006, Measuring the Electrical Properties of Soil using a Calibrated Ground-Coupled GPR System, Vadose Zone Journal, submitted.

Oden, C. P., and Moulton, C. W., 2006, GP Workbench Manual: Technical Manual, User's Guide, and Software Guide, USGS Open-File Report XXXXX, in review.

8. INTERACTIONS AND PRESENTATIONS

Field work was conducted at the Idaho National Laboratory at the invitation of Mr. Gail Heath of INL.

In addition to the meetings and publications cited above, a presentation was given at the 2003 EMSP Workshop at the Pacific National Laboratory in May, 2003 and can be viewed at http://www.pnl.gov/emsp/fy2003/presentations/wright_david_86992.pdf.

9. FUTURE WORK

The existing GPR prototype and methods are available for use at DOE sites, although we do not have specific arrangements made for further deployments at the present time.

10. ACKNOWLEDGEMENTS

We thank Mr. Gail Heath for not only the invitation, but for making the arrangements that made it possible for us to demonstrate and test at the Idaho National Laboratory.

11. DISCLAIMER