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CROSS-WELL RADAR I: EXPERIMENTAL SIMULATION OF CROSS-WELL TOMOGRAPHY AND VALIDATION

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ABTRACT

This paper explains and evaluates the potential and limitations of conducting Cross-Well Radar (CWR) in sandy soils. Implementing the experiment and data collection in the absence of any scattering object, and in the presence of an acrylic plate (a representative of dielectric objects, such as DNAPL (dense non-aqueous phase liquid) pools, etc.), as a contrasting object in a water-saturated soil is also studied. To be able to image the signature of any object, more than one pair of receiving and transmitting antennas are required. The paper describes a method to achieve repeatable, reliable, and reproducible laboratory results for different transmitter-receiver combinations. Different practical methods were evaluated for collecting multiple-depth data. Similarity of the corresponding results and problems involved in each method are studied and presented. The data show that the frequency response of a saturated coarse-grained soil is smooth due to the continuous and dominant nature of water in saturated soils. The repeatability and potential symmetry of patterns across some borehole axes provide a valuable tool for validation of experimental results. The potential asymmetry across other borehole axes is used as a tool to evaluate the strength of the perturbation on the electromagnetic field due to hidden objects and to evaluate the feasibility of detecting dielectric objects (such as DNAPL pools, etc.) using CWR. The experimental simulation designed for this paper models a real-life problem in a smaller scale, in a controlled laboratory environment, and within homogenous soils uniformly dry or fully water-saturated, with a uniform dielectric property contrast between the inclusion and background. The soil in the field will not be as homogenous and uniform. The scaling process takes into consideration that as the size is scaled down; the frequency needs to be scaled up. It is noteworthy that this scaling process needs to be extensively studied and validated for future extension of the models to real field applications. For example, to extend the outcome of this work to the real field, the geometry (antennas size, their separation and inclusion size) needs to be scaled up back to the field size, while soil grains will not scale up. Therefore, soil, water and air coupling effects and interactions observed at the laboratory scale do not scale up in the field, and may have different unforeseen effects that require extensive study.

CE Database subject headings: Radar; Antennas; Saturated Soil; Computerized Simulation; CWR; GPR; Cross-Tomography

BACKGROUND

Ground penetrating radar (GPR) and cross-well radar (CWR, otherwise known as cross-borehole GPR) are radar-based geophysical techniques that can be implemented in a vast variety of applications such as forensics, safety, security, civil infrastructure, and geoenvironmental engineering. Bradford and Wu (2007) successfully used GPR to detect contaminated shallow soils. While GPR is the least invasive radar-based method, it is not a practical one for deep investigations. CWR may be a more effective method for applications such as deep contaminant detection. The complex resistivity (CR) method is another technique that has shown strong potential so far for DNAPL detection as well (Blackhawk Geoservices 2001).

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Cross-well radar (CWR) is essentially the same as surface reflection GPR, except that it uses electromagnetic (EM) transmitting and receiving antennas installed in boreholes. The transmitting antenna propagates EM waves through the medium. Any scattering object with contrasting dielectric properties with respect to the background medium can reflect or scatter the wave. The wave propagation can also speed up or slow down due to this contrast, since $v = c / \sqrt{\varepsilon' \mu'}$, where v and c are respectively the electromagnetic wave (EM) wave velocity in the medium and free-space, ε' and μ' are respectively the real relative dielectric permittivity and relative magnetic permeability of the medium.

The measured data can be in the form of travel time (as with most GPR equipment) or frequency-response (magnitude and phase). Surface reflection GPR only measures the reflected portion of EM waves while CWR can measure reflected and scattered as well as transmitted portions of EM energy.

Growing interest in cross-well methods and applications is evident in a special issue of *Geophysics* (Rector 1995). Early applications of CWR surveys (also labeled geotomography) were reported by Lawrence Livermore National Laboratory (Lager and Lytle 1977; Daily and Lytle 1983; and Daily and Ramirez 1984). CWR can be used along with static and dynamic imaging. Dynamic imaging can be applied to the collected cross-well tomography measurements to identify preferential flow paths and can help characterize complex aquifer heterogeneity (Lane et al. 2000).

Preliminary experimental research and numerical simulation by a finite-difference time-domain (FDTD) method by the authors (Farid et al. 2003) demonstrate that the locations of the transmitting and receiving antennas are vital for detection, due to spatial variations in object signature strength. These locations are the key antenna positions for sensing subsurface objects. Unfortunately, due to lack of information about the nature, shape, and location of these objects, there is little information about the optimum antenna positions. Therefore, there is a need for an efficient antenna installation pattern to cover these key positions optimally in order to collect enough data to construct images of the objects. Potential implementation of CWR in geotechnical and geoenvironmental applications requires deployment of an optimum number of antenna boreholes to balance the trade-off between image accuracy and the extent of the covered area, and to minimize the risk of drilling through contaminated zones. This requires enough knowledge about key positions in the scattered field due to the object and appropriate 3D antenna installation patterns. One popular pattern of antenna installation is cross- tomography, in which the transmission measurements across different boreholes on a circle around the object are collected. Multiple transmitter and receiver locations at multiple depths constitute the antenna pattern to enrich the data pool.

The tomogram and tomography phenomena were first used in medical applications, as a powerful subsurface imaging technique for a vast range of applications. A tomogram refers to a slice or section imaged by moving the transmitter (e.g., X-ray tube) and receiver (e.g., recording film) simultaneously and in opposite directions. Most radar tomography studies have been on 2D cross-well methods and only few exist on 3D applications (Eppstein and Droughty 1998). Olsson et al. (1992) describe an example of 2D cross-well tomography.

Fundamental theoretical and experimental forward modeling knowledge of EM wave propagation and scattering are crucial to study CWR. Different approaches can be pursued to simulate the problem both experimentally and theoretically. This paper addresses the challenges and feasibility of experimental cross-well tomography data collection for later comparison with a first order Born approximation simulation of the problem in the frequency domain (for more information refer to Zhan et al. 2007). Clearly, collecting reproducible and reliable data is the first step of every experimental research. The effort described in this paper is to resolve the problems and challenges in achieving reproducible cross-tomography experimental data and to validate the feasibility of the technique. These issues and challengesare not specific to this experimental work and exist in other experimental and field works in other EM and non-EM sensing modalities used to detect other subsurface objects such as landmines, tunnels, DNAPLs, and engineered structures. Similarly, the proposed solutions are or can be applied to other fields as well.

EXPERIMENTAL METHODOLOGY AND VALIDATION

Experimental Setup and Instruments

A laboratory testing facility (referred to as SoilBED) was constructed for controlled testing of underground subsurface imaging. The facility is used for pilot-scale testing, characterization of soil, and validation of antennas and instrumentation. The details and components of the SoilBED experimental setup are presented in Farid et al. (2006). The setup is 1.5 m by 1.2 m by 2.75 m. The soil selected for the SoilBED is a uniform SP (poorly graded sandy soil) as a representative of a typical aquifer soil. The soil characteristics are presented in Table 1. The soil hydraulic conductivity (k) is 0.01 cm/s, which allows water saturation and drainage in a short period (less than an hour for this setup). To facilitate water saturation and drainage, a perforated PVC piping network was constructed at the bottom of the cell. This drainage system was covered by a fabric filter, buried within a layer of gravel, and then separated from the main soil body by another geotextile fabric. Significant time, effort, and extreme caution were required to deposit the soil uniformly, loosely and with no compaction to achieve a homogeneous soil medium. This is required, as the first step of the research, to develop and evaluate the feasibility of the technique in a controlled environment. The field conditions are not homogenous, and hence, future experimental work should be implemented in heterogeneous conditions. This selection of homogeneous controlled soil medium for the experiment will create more challenges in the comparison efforts with theory and the derivation of the channel transfer function (CTF) introduced by the authors for comparison purposes in a different paper. Since, the CTF derivation uses an assumption based on homogeneity at this stage (for more information refer to Zhan et al. 2007). This will be the biggest challenge of the future works.

The hardware consists of: (a) an Agilent vector network analyzer (VNA) model [8714ES] with an operation frequency band of 0.3 MHz – 3 GHz; (b) a 12-channel Agilent multi-port test-set model [87050E] working in the frequency range 3 MHz – 2.2 GHz, used for cross-well tomography data collection; (c) eight ferrite-bead jacketed monopole antennas with 5 cm long exposed center conductors and dielectric material (for more information, refer to Farid et al. 2006); and (d) PVC casings. In terms of measurement uncertainty and errors, the VNA has a nominal reflection tracking of 0.02 dB and transmission tracking of 0.055 dB for measurements made using "fine" bandwidth, without averaging, and at an environmental temperature of 25° ± 5° C, with less than 1° C deviation from the calibration temperature, provided full 2-port calibration is practiced. The devices and antennas were validated in a previous work by comparing the dielectric permittivity and electric conductivity of a known sandy soil material using different methods (for more information, refer to Zhan et al. 2007 and Kurson 2006). A wideband stepped-frequency analysis produces a representative frequency response of the soil to assess the advantages and limitations of transmission and coupling of different individual frequencies through soil and antennas. The technique is studied at higher frequencies (center frequency of 1.3 GHz) at a space scale of 1/100. It is believed that the size can be scaled up to real field size along with scaling down the frequency to a lower center frequency. This scaling process can be nonlinear. The detection resolution will also decrease. In other words, the size of the smallest detectable scatterer will scale up as well. Even though, in the scaling process, the object size, and antennas size and separation will be scaled up as the frequency is scaled down; soil particles cannot be scaled. There may be scattering due to the soil particles in this pilot-scale experiment, which will not occur in the real-field case. The scaling process and related issues are of great importance and concern and need to be addressed and validated via laboratory and field experiments in the future, since they are beyond the scope of this paper. PVC casings with PVC bushings are used to hold each antenna centered in its casing. Ferrite beads are used to eliminate the wave leakage along the feed cable.

Data Collection

To collect enough datasets to reconstruct images of soil background and scatterers, the EM field should be measured at key positions with strong scattered field magnitude. Since these key points are not known, an optimum pattern of antennas installation is required. A popular one is a cross-tomography pattern with multiple transmitter-receiver locations at multiple depths. Eight PVC-cased boreholes are installed on the perimeter of a circle with 30.5 cm diameter in the SoilBED. For one transmitter (T) located in each borehole, a single reflection measurement (S_{11}) and seven transmission measurements (S_{21}) to seven receivers (R) in the other boreholes are available. Three different depths of 22.9 cm, 27.9 cm, and 33.0 cm are selected for the transmitters and receivers to simulate multiple-depth data collection, which results in nine depth-combinations. These depths are simply selected to simulate a 1/100 scale

field problem. In other words, the depth increment was the main selection based on the size of the antenna (extended dielectric of the monopole antennas = 2" (5.1 cm)). For a perfectly homogenous soil background with a flat ground surface, the response of T_i to R_j is theoretically equal to that of T_j to R_i. This would reduce the depth combinations from nine to six. However, homogeneity is not necessarily guaranteed in the experiment, so all of the nine background (soil only) depth-combinations were collected to validate the measurements and confirm the soil background uniformity and reciprocity.

For the cases involving buried scattering objects or volumes, such uniformity is available only if the scatterer is located in a symmetric position with respect to the antennas. Hence, all nine depth-combinations are necessary, making a total of 576 (8 x 8 x 9) datasets for each background (soil only) or scattered case. A schematic plot of the cross-tomography setup is shown in Fig. 1. To avoid moving the antennas between the boreholes and to enhance the data collection speed, a 12- channel multiport test-set device (Model 87050E) is used. Some steps and processes that have been adopted to improve the data collection procedure and validation are explained by Farid et al. (2006) and are summarized below.

There are two alternative methods to collect data from multiple depths (Fig. 2): (i) install boreholes and casings at the same depths as antennas for each depth increment, and (ii) drill boreholes and install casings to the maximum required depths and install antennas at any desired depth. Transmission measurements are collected using both methods for relatively dry sand (air-dried to 3.9% moisture content, referred to as "drier sand") and close to fully water-saturated sand (16.9% moisture content, referred to as saturated sand), and compared. The transmission measurements were collected at the same antenna depths, while boreholes were driven to the different borehole-depth-configurations of Fig. 2, and the results were compared in Figs. 3 and 4. Figs. 3 and 4 show that there are no significant differences between the results of the three installation methods in the drier and saturated soils, respectively. This can be explained by the low dielectric contrast of the air below the PVC pipes and the fact that very little EM field is radiated in the borehole volume below the lower antenna pole (null direction of the Z (vertically) polarized monopole antennas).

EXPERIMENTAL RESULTS AND DISCUSSIONS

Soil Background Uniformity

Since measurements are collected across boreholes that are located on a circle in a controlled homogenous soil medium, the scatterer-free soil background data is theoretically expected to be symmetric with respect to T/R pairing. However, while symmetry is a good way of validating all soil background data sets, achieving the desired symmetric soil background data in practice is challenging. A template is used to obtain accurate antenna locations on the cross-tomography circle and ensure the antenna alignment. Fig. 5 shows the template and borehole-numbering layout. The template has two sets of holes on two circles with two different diameters (12" (30.5 cm) and 16" (45.7 cm)). In this paper, only the inner circle was used.

Background (soil only) electrical field measurements were collected in the drier and saturated soils. Boreholes and PVC casings were installed precisely vertically at the desired locations and down to the maximum desired depth. Installing the PVC-cased boreholes in the soil disturbs the soil homogeneity and creates compacted dense or less compacted loose zones. However, due to lower dielectric contrast between the drier soil (ε'$_{Drier\ soil}$ ≈ 4.5 to 4.42 at the frequency range of: f = 0.4 GHz to 2.2 GHz) and air (ε'$_{Air}$ = 1), the inhomogeneities do not substantially affect the symmetry in the drier soil. In the saturated soils, however, the greater difference between the dielectric constant of water (ε'$_{Water}$ ≈ 77 to 80 at the frequency range of: f = 0.4 GHz to 2.2 GHz (von Hippel 1954)) and the saturated soil (ε'$_{Saturated\ Soil}$ ≈ 20.6 to 20 at the frequency range of: f = 0.4 GHz to 2.2 GHz (Zhan et al. 2007 and Kurson 2006)), is expected to result in stronger field variations when the soil is disturbed. It is noteworthy that both the dielectric permittivity values for water and the saturated soil vary over the frequency range.

To reduce the soil heterogeneity caused by borehole installation, the SoilBED was saturated and drained several times before starting each set of background (soil only) or scattered case experimentation. This was simply observed in an experiment where the drainage recharge process lowered the error between measurements collected at identical geometries at two different locations by improving the uniformity of the soil (for more information, refer to Farid et

al. 2006). Furthermore, the soil surface was graded to eliminate non-symmetric reflections from soil-air interface roughness.

This is an attempt to simulate a controlled homogeneous soil condition in the laboratory for the initial steps of the research. The field conditions are not homogeneous. The issue of soil background heterogeneity is the greatest challenge of any geophysical investigation and needs to be addressed in the future.

In this study, -2 dB to +2 dB is considered the acceptable margin of error (caused by soil heterogeneity) between potentially identical measurements due to geometrical symmetry. The acceptable error margin of 2 dB was selected based on the observations of the error between measurements collected at two equivalent points in the uniform soil in a previous experiment. Increasing the separation between the transmitting and receiving antennas decreases the transmitted energy level and increases errors of this type. Fig. 6 shows the potentially identical (due to symmetry) measurements collected in the drier and saturated soils with the transmitter depth of 22.9 cm and receiver depth of 33.0 cm, as well as the difference (error) between the measurements. In the figures, *T* represents the transmitter and *R* represents the receiver (e.g., *T1-R3* means the transmitter located in Borehole 1 and the receiver in Borehole 3). Due to the lossy nature of water and saturated soils, the power transmitted through the saturated soil is lower than through the drier soil. Therefore, transmitted signals (at the same antennas separation) through the saturated soil are weaker than the ones in the drier soil. In addition, the signal to noise ratio in the saturated soil is lower than in the drier soil. This leads to higher errors of the abovementioned nature in the saturated soil. This error is more pronounced at higher frequencies due to the higher sensitivity of small objects to shorter wavelengths.

There are nine depth-combinations for the three selected depths. Background (soil only) symmetry was studied for all different transmitter and receiver depth-combinations in the drier and saturated soils. Any increase in the depth difference between the antennas results in an increase in the overall antennas separation (along the slope) for a constant horizontal antenna separation. Therefore, the repeatability errors are greater for greater depth differences between the transmitter and receiver antennas.

Reciprocity was also assessed for transmission between antennas at different depths in the saturated soil condition. For example, the background (soil only) transmission measurements should be reciprocal when: (i) transmitter depth = 22.9 cm and receiver depth = 27.9 cm, or (ii) transmitter depth = 27.9 cm and receiver depth = 22.9 cm. This is confirmed in Fig. 7, except for higher frequencies where the signal to noise ratio is extremely low.

Scattered Field, Symmetry, and Asymmetry Issues

To evaluate the effect of the material, size and thickness of scattering objects on the EM field in saturated soils, the scattering effect of acrylic objects of different sizes on the EM field was studied in soil; only one case among those is presented in this paper. As mentioned before, significant efforts were applied to achieve soil homogeneity during and after installation of the scatterers to guarantee achieving identical results at identical locations (due to symmetry) across the axis of symmetry of the geometry of scatterer positioning (Axis 2-6, Figs. 5 and 8). Although the PVC-cased boreholes and their surrounding soils were not disturbed, the soil within the circle was removed, the scatterers were precisely emplaced, and the soil was replaced. To ensure that the surrounding soil is as close as possible to the original background (soil only) case before the scatterer installation process, the soil was saturated and drained several times after the scatterer placement. This was necessary to eliminate any inhomogeneities caused by the installation process. To achieve correlation with homogenous soil conditions, this preparation process should be conducted with extreme care. The object evaluated in this study is an acrylic plate (8.9 cm x 8.9 cm x 0.5 cm). Acrylic was selected as a dielectric object ($\varepsilon' \approx 2.6$) similar to pure DNAPL (typical DNAPLs ≈ 2.3) (Weast 1975). However, DNAPLs mixed with soil and water may have a different dielectric constant as the result of mixture (Ajo-Franklin et al. 2004). A schematic of the top view of the scatterer in the soil is shown in Fig. 8. The plate is located symmetrically with respect to Axis 2-6, and off center within the cross-tomography circle.

Symmetry in Scattered Field:

Typical results are compared for the scatterer at the depth of 27.9 cm in the saturated soil with the antennas installed at multiple depths. The comparisons show the symmetry across Axis 2-6 and asymmetry across other axes. The transmission measurements across the following boreholes should be respectively identical due to the symmetry between axes: 2-1 versus 2-3, 2-4 versus 2-8, and 2-5 versus 2-7. Fig. 9 shows the measurements across some of the

symmetric axes and the corresponding error (the difference between these measurements) for transmitter and receivers at the same depth. Fig. 10 shows a similar set of results for the transmitter and receivers at different depths. As seen in Figs. 9 and 10, these potentially identical (due to symmetry) measurements in the background soil are very close. However, the results show that increasing antennas separation decreases the energy level, which in turn increases the error (difference between measurements across symmetric axes). Moreover, increasing the depth difference between transmitting and receiving antennas increases the interference by the soil-air interface, which is observed by comparing Figs. 9 and 10.

Asymmetry in Scattered Field:

The acrylic object was specifically positioned such that it selectively creates asymmetry along some axes to provide enough data for future inversion and image reconstruction purposes. Figs. 11 and 12 demonstrate that the scattering response (transmission response with the scatterer - transmission response without the scatterer) is strong enough to create asymmetry across the axes that are asymmetric at the presence of the scatterer but potentially symmetric in the absence of the scatterer (background: soil only). Fig. 11 shows the scattered fields across Axis 1-3 and Axis 5-7, where the transmitter and receivers are at the same depth, and the difference between the two measurements caused by the asymmetric positioning of the scatterer with respect to the two axes. Fig. 12 shows similar results to Fig. 11 with the exception that the transmitter and receivers are located at different depths. In these asymmetric cases (Figs. 11 and 12), the scatterer response is stronger than the error in the symmetric background (soil only) measurements (Figs. 9 and 10). This scattering response varies over the frequency range as both up and down shifts. This may be caused by the variations of the dielectric permittivity contrast between the soil and acrylic along the frequency range (acrylic is not dispersive, but soil is). It can be stated that the strong difference between the measurements across the asymmetric axes (because of the presence of scatterer) is representative of the strength of the scattering response and in turn a supporting fact for the feasibility of the detection. As expected, this difference is less visible at lower frequencies due to the lower sensitivity of small object to low frequency (long wavelength) waves.

The real-field problem has been scaled up in frequency and down in size to create this experimental model. In this experiment, the resonance-frequency of the transmitting and receiving antennas (1.1 GHz) is designed high enough to detect the scaled-down object size. Frequencies lower than this designed resonance-frequency may not be able to detect the object in the experimental simulation. Field antennas are larger and have lower resonance-frequency to detect larger field objects. Accordingly, frequencies much lower than the field resonance-frequency may be too low to detect the real-field objects.

Both antennas positioned at the same depth as the scatterer (Fig. 11) show a stronger detection potential than the antennas at two different depths each different from the depth of the scatterer (Fig. 12). This is an interesting observation, which may vary based on how the object is placed or, in other words, how EM waves cross the object (whether the wave crosses a larger object surface or a more significant object thickness).

The other tool to distinguish the scattered case from background (soil only) is the difference between two sets of data acquired by depth profiling across symmetrical geometries. Fig. 13 studies this within the saturated soil. To simulate this invisible asymmetry in geometry in the absence of the scatterer, it is important to locate the scatter at a different horizontal distance to the transmitter than to the receiver. If the antennas are at two different depths and the object is located *asymmetrically* between them (e.g., off the center of the circle along Diagonal 2-6 in Fig. 8), switching the depth of the transmitter and receiver will make a difference in the scattered field, due to asymmetry. This has no effect on the background (soil only) field, due to symmetry. In order to be able to utilize this logic, the scatterer should be located in an asymmetric position between the two antennas (as shown in Fig. 13). Otherwise, the scattered results will be identical. Therefore, this fact is valid for Diagonal 2-6, but not valid for other axes such as Axes 1-4, 2-7, and 3-8 as shown in Fig. 8.

It is important to note the difference between this phenomenon and the act of switching the VNA from S_{21} (transmission from Antenna 1 to Antenna 2) to S_{12} (transmission from Antenna 2 to Antenna 1) while the location of Antennas 1 and 2 are not changed. S_{21} and S_{12} measurements are always identical and reciprocal in any background (soil only) or scattered case. In other words, S_{21} and S_{12} measurements for fixed antennas are always the same for both background (soil only) and scattered fields. Consider the two antennas that are installed in Boreholes 2 and 6 at depths 27.9 cm and 33.0 cm. If the transmitter and receiver locations are switched, the two sets of background (soil

only) data should be the same due to symmetry while the scattered observations should be different. The two identical background (soil only) results as well as the error between the two are shown within the saturated soil in Fig. 14. The scattered results and the difference between the two measurements (due to the presence of the scatterer) are shown in Fig. 15. As seen in Figs. 14 and 15, the errors between the geometrically identical background (soil only) measurements (Fig. 14) are smaller and in the form of one-way shifts (either up or down over the entire frequency range). On the other hand, the differences between the scattering responses for the measurements of Fig. 15 are more pronounced and visible as both up and down shifts throughout the frequency range. Again, in Fig. 15 (similar to the case of Fig. 13), these differences are less visible at lower frequencies (frequencies too low for the scaled-down object size, which are the ones lower than the designed resonance-frequency of the antennas in this experiment). Apparently, for the field, the resonance-frequency needs to be scaled down, and the object scaled-up. Accordingly, in the field, there are lower frequencies (lower than the designed resonance-frequency of the antennas) that are not capable of detecting the predictable field object size.

CONCLUSIONS

In the background (soil only) field, the visible symmetry in the geometry is valid for the measurements. However, this is not valid for the scattered field due to the presence of the hidden scatterer. This difference between the measurement with and without the presence of the scatterer provides a strong support for the validity of the measurements and feasibility of the detection method for the highly uniform sample. The off-center and asymmetric positioning of the target across some axes connecting boreholes provides more information than a symmetric centric positioning for future image reconstruction. The strength of the scattered field (difference between incident and total fields) supports the feasibility of the use of the CWR technique to detect dielectric objects such as DNAPL pools, tunnels, etc. Symmetry and asymmetry across different axes connecting boreholes due to geometry can verify some inaccuracies in the measurements. However, in order to use the measurement for inversion and reconstruction, a validated forward model is necessary. To validate any proposed forward model, the theoretically simulated and experimentally measured data need to be compared. The comparison cannot be possible unless the two are compatible. Comparison between the experimentally simulated results of this paper with a theoretical simulation (forward model) will help to provide a validated forward model for future inversion and image reconstruction. As in most other research areas, the two may not be immediately comparable. Necessary transformations should be applied to make the two compatible. The necessary transformation is presented in another paper by the authors.

The work can be extended to study real-life problems, such as contaminant detection and monitoring. However, there are issues that need to be studied before the outcome is extended. The experimental simulations of this work models a real-life problem in a pilot-scale, and hence, at a higher frequency. Besides, the medium is a homogenous soil medium and in a controlled environment, with a uniform dielectric property contrast between the inclusion and background. The assumption has been the validity of a linear scaling relation between the size and frequency. The frequency was scaled up from the field inversely proportional to how the geometry of the problem (antennas size and separation, soil medium extent, and inclusion size) was scaled down. The only component that does not contribute to this scaling process accordingly, is the size of soil-grains, which can affect the coupling between the soil and antennas. Therefore, this scaling process needs to be extensively studied and validated, before the outcome of this work is extended to field applications

NOTATIONS

f = frequency;
S_{11} = Reflection measurements at Port 1;
S_{22} = Reflection measurements at Port 2;
S_{21} = Transmission measurements from Port 1 to Port 2;
S_{22} = Transmission measurements from Port 2 to Port 1;
ε = Dielectric permittivity;
ε' = ε_r = Relative dielectric permittivity (dielectric constant);
σ = Electric conductivity; and
ω = Temporal angular frequency, and conjugate to time (t) in the frequency domain.

REFERENCES

Ajo-Franklin, J. B., Geller, and Harris, J. M. (2004). "The dielectric properties of granular Media saturated with DNAPL/water mixtures." *Geophysical Research Letters*, 31(17), L17501.

Blackhawk Geoservices Inc. (2001). *Integrated geophysical detection of DNAPL source zones*. Final report, < http://handle.dtic.mil/100.2/ADA409159>, (last accessed February 2008).

Bradford, J. H., and Wu, Y. (2007). "Instantaneous spectral analysis: Time-frequency mapping via wavelet matching with application to 3D GPR contaminated site characterization." *The Leading Edge*, 26, 1018-1023.

Daily, W., and Lyte, J. (1983). "Geophysical tomography." *Journal of Geomagnetism and Geoelectricity*, 35, 423-442.

Daily, W. D., and Ramirez, A. L. (1984). "In situ porosity distribution using geophysical tomography." *Geophysical Research Letters*, 11, 614-616.

Eppstein, M. J., and Dougherty, D. E. (1998). "Efficient three-dimensional data inversion: Soil characterization and moisture monitoring from cross-well ground-penetrating radar at a Vermont test site." *Water Resources Research*, 34(8), 1889–1900, August.

Farid, M., Alshawabkeh, A. N., and Rappaport, C. M. (2003). "Modeling borehole dipole antenna patterns for cross-well radar DNAPL imaging." *Electronic Proceedings of the 12th Pan-American Conf. on Soil Mech. and Foundation Engineering*, Cambridge, MA.

Farid, M., Alshawabkeh, A. N., and Rappaport, C. M. (2006). "Calibration and validation of a laboratory experimental setup for CWR in sand." *ASTM*, *Geotechnical Testing Journal*, 29(2), 158-167 (March).

Kurson, C. (2006) "Minimally invasive microwave measurements for modeling of a sandy soil properties." Master's thesis, Northeastern University, Boston, MA.

Lager, D. L., and Lytle, R. J. (1977). "Determining a subsurface electromagnetic profile from high frequency measurements by applying reconstruction algorithms." *Radio Science*, 12, 249-260.

Lane, J. W., Wright, D. L., and Halni, F. P. (2000). "Borehole radar tomography using saline tracer injections to image fluid flow in fractured rock." *Profiles of Federally Funded Projects*, EPA 542-R-98-020, <http://water.usgs.gov/ogw/bgas/imaging>, (last accessed in Jan 2003).

Olsson, O., Falk, L., Forslund, O., Lundmark, L., and Sandberg, E. (1992). "Borehole radar applied to the characterization of hydraulically conductive fracture zones in crystalline rock." *Geophysical Prospecting*, 40, 109–142.

Rector, J. W. (1995). "Cross-well methods: Where are we, where are we going?" *Geophysics*, 60(6), 629–630.

von Hippel, A. R. (1954). *Dielectrics materials and applications*. MIT Press, Cambridge, MA.

Weast, R. C. (1974-1975). *CRC Handbook of Chemistry and Physics*, 55th edition, CRC Press, Cleveland, OH.

Zhan, H., Farid, A. M., Alshawabkeh, A. N., Raemer, H., and Rappaport, C. M. (2007). "Validated half-space Green's function formulation for Born approximation for cross-well radar sensing of contaminants." *IEEE, Transaction of Geoscience and Remote Sensing*, 45(8), 2423-2428, August.

Fig. 1. Cross-well tomography setup: (a) cross-tomography antenna placement in SoilBED facility, (b) single transmitter at Borehole 1 and receivers at Boreholes 3, 4 and 7, (c) cross-well tomography in SoilBED facility, and (d) vector network analyzer model 8714ES (top), multiport test-set model 87050E (bottom)

Fig. 2. Different alternatives to install borehole and antenna at variable depths: (a) one borehole driven to the required depth and the other one deeper, (b) both boreholes driven to the depth required for each increment, and (c) both boreholes driven to the ultimate depth for future use, which is deeper than required for this increment

Fig. 3. Transmission measurements for 8" (20.3 cm) antenna separation in drier soil, transmitter depth = 9" (22.9 cm), and receiver depth = 7" (17.8 cm); within boreholes of different depths: 11" (27.9 cm), 9" (22.9 cm), and 7" (17.8 cm)

Fig. 4. Transmission measurements for 8" (20.3 cm) antenna separation in saturated soil, transmitter depth = 9" (22.9 cm), and receiver depth = 7" (17.8 cm); within boreholes of different depths: 11" (27.9 cm), 9" (22.9 cm), and 7" (17.8 cm)

Fig. 5. Experimental setup: (a) cross-tomography template and (b) typical top view of the cross-well tomography circle, and borehole numbering

Fig. 6. Potentially identical background (soil only) results due to geometrical symmetry collected at transmitter depth of 27.9 cm, receiver depth of 33.0 cm, antenna locations of 1-3, 4-6 and 7-1 (8.5" (21.6 cm) antenna separation), for: (a) drier soil, (b) saturated soil; and the difference between the three potentially identical measurements (error with respect to the first one) for: (c) drier soil, (d) saturated soil

Fig. 7. Reciprocity of background (soil only) transmission measurements at reciprocal transmitter and receiver depths (9" (22.9 cm) and 11" (27.9 cm)) in Boreholes 7 and 8 (4.6" (11.7 cm) antenna separation): (a) potentially identical measurements, (b) difference between the two potentially identical measurements (error)

Fig. 8. Top view of the acrylic plate location in the soil

Fig. 9. Symmetry of scattered field across Diagonal 2-6; depths of both transmitting and receiving antennas = 11" (27.9 cm), for transmission along Axis 2-1 versus Axis 2-3 (4.6" (11.7 cm) antenna separation): (a) potentially identical measurements, (b) difference between the two potentially identical measurements (error)

Fig. 10. Symmetry of scattered field across Diagonals 2-6; depth of transmitting antenna = 11" (27.9 cm) and depth of receiving antennas = 13" (33.0 cm), for transmission along Axis 2-1 versus Axis 2-3 (4.6" (11.7 cm) antenna separation): (a) potentially identical measurements, (b) difference between the two potentially identical measurements (error)

Fig. 11. Asymmetry of scattered field across diagonal axes other than 2-6; depths of both transmitting and receiving antennas = 11" (27.9 cm), 8.5" (21.6 cm) antenna separation: (a) measurements, (b) scatterer response (i.e., difference between the two due to asymmetric positioning of scatterer)

Fig. 12. Asymmetry of scattered field across diagonal axes other than 2-6; depth of transmitting antennas = 11" (27.9 cm) and depth of receiving antennas = 13" (33.0 cm), 8.5" (21.6 cm) antenna separation: (a) measurements, (b) scatterer response (i.e., difference between the two measurements due to asymmetric positioning of scatterer)

Fig. 13. Schematic of antennas, scatterer locations and depths that provides depth asymmetry for scattered case

Fig. 14.   Reciprocal background (soil only) transmission measurements at multiple depths, Boreholes 2 and 6, 12" (30.50 cm) antenna separation: (a) Potentially identical measurements, (b) Difference between the two potentially identical measurements (error)

Fig. 15.   Non-reciprocal scattered transmission measurements at multiple depths, Boreholes 2 and 6, 12" (30.50 cm) antenna separation: (a) measurements, (b) scatterer response (i.e., difference between the two measurements due to asymmetric positioning of scatterer)