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A Laboratory Approach Relating Complex Resistivity Observations to Flow and Transport in Saturated and Unsaturated Hydrologic Regimes (Tracking Code: 01-FS-006)

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U.S. Department of Energy

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Introduction

Subsurface imaging technology, such as electric resistance tomography (ERT), is rapidly improving as a means for characterizing some soil properties of the near-surface hydrologic regime. While this information can be potentially useful in developing hydrologic models of the subsurface that are required for contaminant transport investigations, an image alone of the subsurface soil regime gives little or no information about how the site will respond to groundwater flow or contaminant transport. In fact, there is some question that tomographic imaging of soils alone can even provide meaningful values of hydraulic properties, such as the permeability structure, which is critical to estimates of contaminant transport at a site. The main objective of this feasibility study was to initiate research on electrical imaging not just as a way to characterize the soil structure by mapping different soil types at a site but as a means of obtaining quantitative information about how a site will respond hydrologically to an infiltration event. To this end, a scaled system of electrode arrays was constructed that simulates the subsurface electrode distribution used at the LLNL Vadose Zone Observatory (VZO) where subsurface imaging of infiltration events has been investigated for several years. The electrode system was immersed in a 10,000-gallon tank to evaluate the fundamental relationship between ERT images and targets of a given volume that approximate infiltration-induced conductivity anomalies. With LDRD funds we have explored what can be initally learned about porous flow and transport using two important electrical imaging methods -- electric resistance tomography (ERT) and electric impedance tomography (EIT). These tomographic methods involve passing currents (DC or AC) between two electrodes within or between electrode arrays while measuring the electric potential at the remaining electrodes. With the aid of a computer-based numerical inversion scheme, the potentials are used to solve for the electrical conductivity distribution in the region bounded by the electrode arrays. Groundwater movement resulting from a leak or surface spill will produce measurable conductivity changes that have been imaged using ERT or EIT. The kind of laboratory scale experiments supported by this work will help us to better understand the connection between imaged conductivity anomalies and the groundwater or contaminant flow that causes them. This work will also help to demonstrate the feasibility or value of doing lab experiments in imaging that can be applied to interpreting field-scale experiments.

A secondary objective of this study was to initiate a collaboration with researchers at the Rensselaer Polytechnic Institute (RPI; Troy, NY) who are also participants in the newly created NSF Center for Subsurface Imaging and Sensing Systems (CenSSIS) which is managed in part by RPI. During the course of this study C.R. Carrigan and W. Daily visited the electromagnetic imaging lab at RPI to initiate discussions on subsurface imaging technology with Professors David Isaacson, Jon Newell, Gary Salunier and their research graduate students. A major goal of CenSSIS is to promote collaborations among researchers with imaging backgrounds in different discplines (geosciences, biomedical, civil engineering and biomedical) that will lead to new solutions of common subsurface imaging problems. The geophysical test section constructed for this study included electrode arrays that resemble biomedical array distributions. Comparing images of the same target produced with the 4-array geophysical approach and with the biomedical imaging approach will help us to better understand differences and advantages that are characteristic of the two imaging methods. Our initial interactions with the researchers at RPI concluded that this was a viable problem to consider. The support for this subsequent research will come from a 3-year Office of Basic Energy Sciences (BES) proposal that has just received funding. This feasibility study contributed positively to the successful review and ultimately to the award of this BES funding. A letter (Appendix) from Professor Michael Silevitch, Director of CenSSIS, to Dr. Rokaya Al-Ayat, Director of the LLNL Science & Technology Office, acknowledges the contribution of this LDRD study to obtaining the Basic Energy Science grant that will fund further work in this area.

The Vadose Zone Observatory

The LLNL VZO is a field-scale site for performing controlled infiltration experiments to study the physics of flow and transport in the vadose or unsaturated zone, that is, in the region lying above the water table. The outstanding need to understand and interpret the images of flow-induced conductivity anomalies obtained from this facility very much motivates the lab tank experiments mentioned above as well as the collaboration with RPI researchers.

The VZO is an example of an intermediate scale facility that is well characterized by field-scale standards and allows a high degree of monitoring of infiltration events. The facility utilizes a variety of monitoring methods to track controlled infiltration experiments. The unsaturated regime at the site is approximately 60-70 feet in thickness and consists of silt, silty-sand and silty-gravel deposits. The observatory consists of almost twenty instrumented boreholes and monitoring wells which traverse the 70-foot unsaturated zone including eight wells containing electric resistance tomography (ERT) arrays and four boreholes with multilevel gas-sampling ports, soil temperature sensors, gypsum blocks, tensiometers and lysimeters (Fig. 1). Several multichannel data loggers continuously store information about surface barometric pressure, subsurface gas-phase pressure, subsurface temperature, capillarity and water-table levels that is downloaded into portable computers for analysis. The facility is ideal for carrying out infiltration experiments designed to elucidate how vadose zone characteristics such as preferential pathways, heterogeneities, multiple phases of flow and relative permeabilities influence the transport of contamination in liquid, gas and colloidal phases to the water table. Using the capabilities of the VZO, we can continuously monitor the progress of an infiltration event. In addition, we can also directly take samples of moisture and gases for analysis at many different depths in the vadose zone as well as from the underlying water table. The ability to sample is critical to our infiltration experiments which include gas- and liquid-phase tracers and tagged particles simulating colloids.

To date a number of infiltration events have simulated leaks from tanks or subsurface pipes such as might have occurred beneath the single-walled tanks at the Hanford Reservation. Either the flow rate or head are controllable from such near-surface point sources. Typical experiments involve the release of 1500 to 80,000 liters of water with typical zero-head injection rates of 2-3 liters/min. The ERT arrays measure electrical conductivity changes resulting from plume-induced chemical changes to the ground water as well as saturation changes. Figure 2 illustrates a typical sequence of ERT images obtained from an early infiltration event. The 3-D images obtained from inversion of the conductivity measurements of the soil bounded by the vertical electrode arrays show structure corresponding to electrical conductivity increases down to the water table. In addition to the vadose zone conductivity enhancements associated with saturation changes, tensiometers detect saturation increases throughout the whole vadose regime. Further, both liquid- and gas-phase tracers have been used to track the downward chemical progression of the plume allowing an interesting comparison to be made with the ERT results.

Simulations of infiltration at the site assuming a multi-layered-soil (i.e., 2-D) structure with hydrologic properties determined from lab tests on soil cores suggest that the vadose zone will function as a formidable barrier to contamination of the water table by a near-surface leak. However, the ERT results show that saturation changes occur down to the water table within hours. Similar results are obtained from gypsum-block tensiometers placed at different levels in a monitoring well near the central infiltration well. A 3-D heterogeneous model with high-permeability pathways more closely fits the observations of rapid saturation change down to the water table than the layered model mentioned above (Carrigan *et al.*, 1998). On the other hand, the results of our attempts to track the migration of chemical tracers across the vadose zone show that a significant time lag (~ one month) exists between the detection of saturation changes near the water table and the detectable arrival of the tracers at the water table. During this interim period, water was infiltrated periodically until approximately one pore volume had been flushed through the vadose zone. The observed amount of infiltration required for large amounts of tracer to arrive at the water table is in excellent agreement with our numerical simulations. We attribute this time-lag between the detection of saturation and chemical changes near the water table to be largely a result of displacement and dilution effects. The one observed exception to the displacement-dilution model of contaminant transport to the water table is the observation that a small amount of tracer (8% of the concentration change observed later) reached the water table within hours of a 1500 liter infiltration event. Such an observation can only be explained hydrologically as a fastpath or preferential pathway capturing a small portion of the injected tracer-laden water and channeling it directly to the saturated zone. ERT observations at the VZO support this view since on at least one occasion, imaging indicated that injected, highly conductive, salt water reached the water table only a few hours after the start of injection (Fig 3). A legitimate issue about subsurface imaging in this kind of field experiment is whether or not we can actually resolve a fast path for contaminant transport as well as what is the smallest fast path that we can resolve with this imaging system. These are the kinds of questions that we want to begin answering with this feasibility study.

Feasibility Study Experiments

Instead of using soil, water contained within a 10,000 gallon tank was used to provide the electrically continuous medium surrounding the four electrode arrays, each having 18 electrodes, that are analogous to the four electrode wells at the Vadose Zone Observatory. Figure 4 illustrates the frame supporting the four attached linear electrode arrays that were constructed for the imaging study. Figure 5 shows the test frame with a conductive porous "long sock" target suspended in the array domain as it is being lowered into the tank prior to an imaging experiment. The "long sock" consists of a porous, cylindrical, sand-filled body with metal shot added to enhance electrical conductivity. The sand and shot combination was adjusted so the conductivity of the water-saturated target was about two times the background electrical conductivity of the tank. This conductivity contrast is comparable to what might be expected for a salt-water saturated region created during a controlled leak into the vadose zone at the LLNL VZO. Several targets were imaged in addition to the long sock including a "short sock" target, metal and plastic cylinders and metal and plastic rectangular plates intended to represent ranges in conductivity contrast and in the shape of possible hydrologic anomalies. No attempt is made to present all the results here. In fact more data was taken than could be reduced within the scope of this feasibility study. However, these imaging experiments will be the basis of a fairly comprehensive manuscript that is being written for a peer-reviewed journal.

The "long sock" was imaged at a variety of vertical and horizontal locations in the test apparatus as shown in Figure 6. Further analysis of these and the other images will be carried out but intial results are encouraging as far as the detection and target location capabilities of the complex resistivity approach are concerned. Figure 6 is an image based on phase information only. Figure 7 shows similar plots of shape and location for a very large resistivity contrast stainless steel cylinder. It is interesting that the electrical ac phase change, which tends to be small (measured in milliradians), produces stronger images than are produced by the magnitude or ohmic part of the complex resistivity which represents a huge contrast in conductivity (i.e., the ratio of the conductivity of stainless steel to water >>1). This is particularly apparent in both the first and last frames of the experiment with the magnitude-based image disappearing at the top and the bottom of the domain while the phase-based image is still apparent.

The results of the cited experiments will be combined with those of other experiments that have yet to be reduced and evaluated to quantify the complex resistivity imaging process for a given domain size and electrode separation. The catalog of targets with their associated images will be useful for interpreting observations such as the magnitude-based conductivity anomaly of Figure 3. The collection of images using various targets having different conductivity contrasts will also provide information about the relationship between the minimum detectable size and conductivity contrast. The results also suggest that more work needs to be done to investigate the advantages of phased-based or complex resistivity imaging (Electric Impedance Tomography) over pure ohmic resistance-based imaging (Electric Resistance Tomography). Most imaging performed at the VZO to date has been of the ERT type. However, our experiments suggest that greater sensitivity may be associated with the EIT or complex resistivity based approach. This is true at least in the case of stainless-steel cylinders which exhibit induced polarization behavior. Comparision using the sand-filled targets will be more useful for hydrologic purposes in evaluating the relative merits of EIT versus ERT.

Suggested Future Research

Out of the work described above and the LDRD supported interactions with RPI researchers have come a series of ideas for future research projects that will now be supported in part by the Basic Energy Science contract that was recently awarded to C.R. Carrigan and others. We will collaborate with Profs. David Isaacson, Jon Newell, Gary Salunier and graduate students of the Electrical Impedance Imaging Laboratory at Rensselaer Polytechnic Institute to carry several bench-scale experiments. With little modification to their existing lab capability, we will explore differences between ERT and the biomedical approach to EIT for subsurface hydrologic measurements. The RPI group has had extensive experience performing and analyzing EIT bench-scale experiments with application to medical imaging using their ACT-3 imaging capability (http://www.rpi.edu/~newelj/eit.html). The ACT-3 System is a 32-channel impedance imaging system for variable frequency electrical impedance tomography. It can apply ac currents to each of 32 electrodes, and record the voltage at each electrode simultaneously. With multiplexing, we can use between 64 and 128 electrodes in an experiment. For a 4-well array of electrodes, such as the LLNL electrode array developed under LDRD funding. The application of electrical current is under software control, so it is possible to have any desired pattern of electrode sampling. In particular, the RPI group has experimented with different current patterns in their biomedical imaging studies that may also have application to our subsurface imaging work. We will apply their algorithms to choose the optimal current patterns in our imaging work.

The planned research with Rensselaer involves exploration of both ERT and EIT techniques using bench-scale experiments with the ultimate goal of enhancing our ability to image the subsurface. ERT techniques have been used most extensively in hydrologic imaging while EIT has been pursued as the electromagnetic imaging method of choice for biomedical purposes. One principal goal of this work will be to answer the question concerning how ERT and EIT complement each other in a heterogeneous soil environment.

Figures

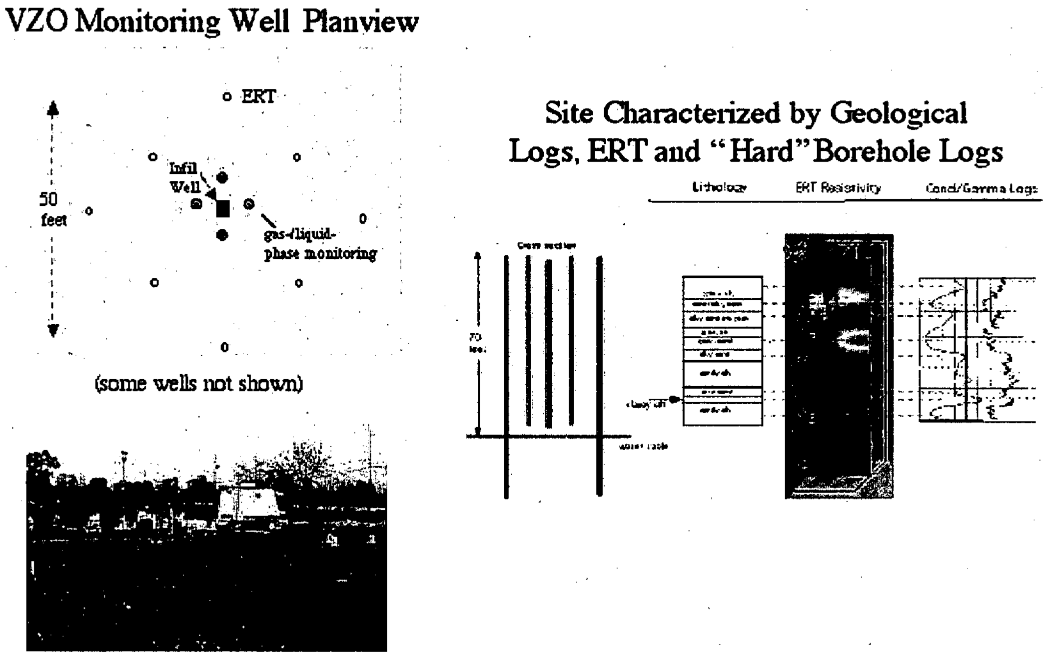
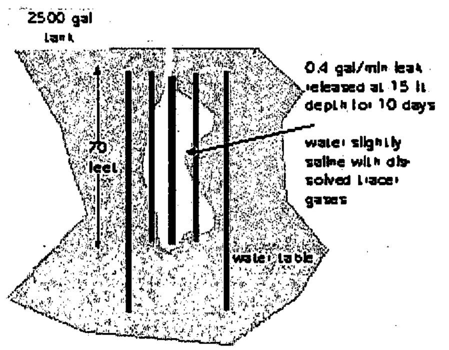


Figure 1.

The LLNL Vadose Zone Observatory developed with support from EMSP (54950) is a well-characterized site with approximately 20 wells containing instrumentation for measuring a variety of parameters relevant to the migration of a plume from a shallow subsurface leak to the water table. Infiltration experiments simulating tank leaks are carried out at this site in a controlled, heavily monitored field environment.



Infiltration Parameters Monitored

* Liquid phase location versus time (ERT/tracers)
* Gas phase location versus time (noble tracers)
* Gas-phase pressure at various depths
* Liquid phase saturation
* Gas & liquid phase sampling

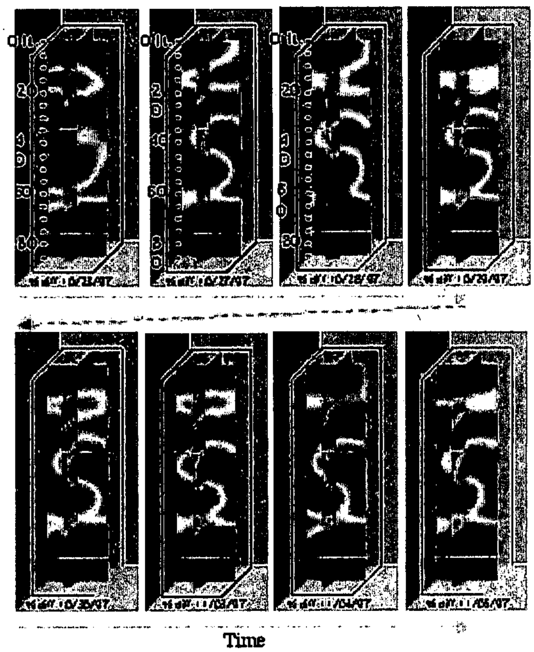
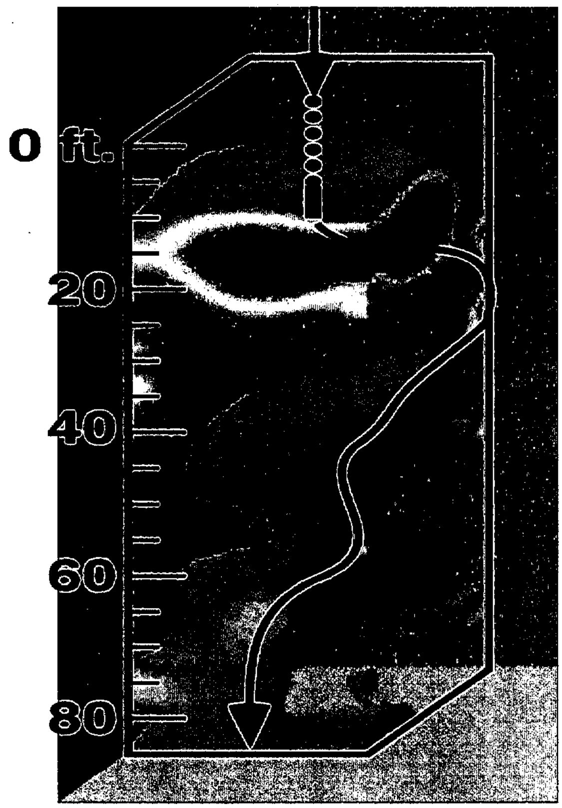


Figure 2

A schematic diagram (upper left) illustrates an infiltration event and the relationship of the infiltration plume to the ERT arrays shown in red. An actual sequence of ERT images is shown over approximately a 24-hour period (right). The oscillation in color (green to blue to green) of the central kidney shaped image is evidently a response to the period voiding of trapped air in the vadose zone. The images which illustrate electrical conductivity change form rapidly down to the water table indicating the the top and bottom of the vadose zone are well-connected hydraulically.

Vadose Zone Observatory
Salt Water Infiltration



Saturation Changes at bottom of VZ in less than 6 hours

Figure 3.

An ERT image showing the electrical conductivity distribution less than 6 hours after a 1500 liter infiltration event using very saline water. The water table is normally below 65-70 feet but the salt water signal appears to have actually penetrated below the watertable owing to its greater density. This result in conjunction with the tracer study in Figure 3 strongly suggests that fast paths can carry at least part of the "contaminated" water rapidly to the water table.

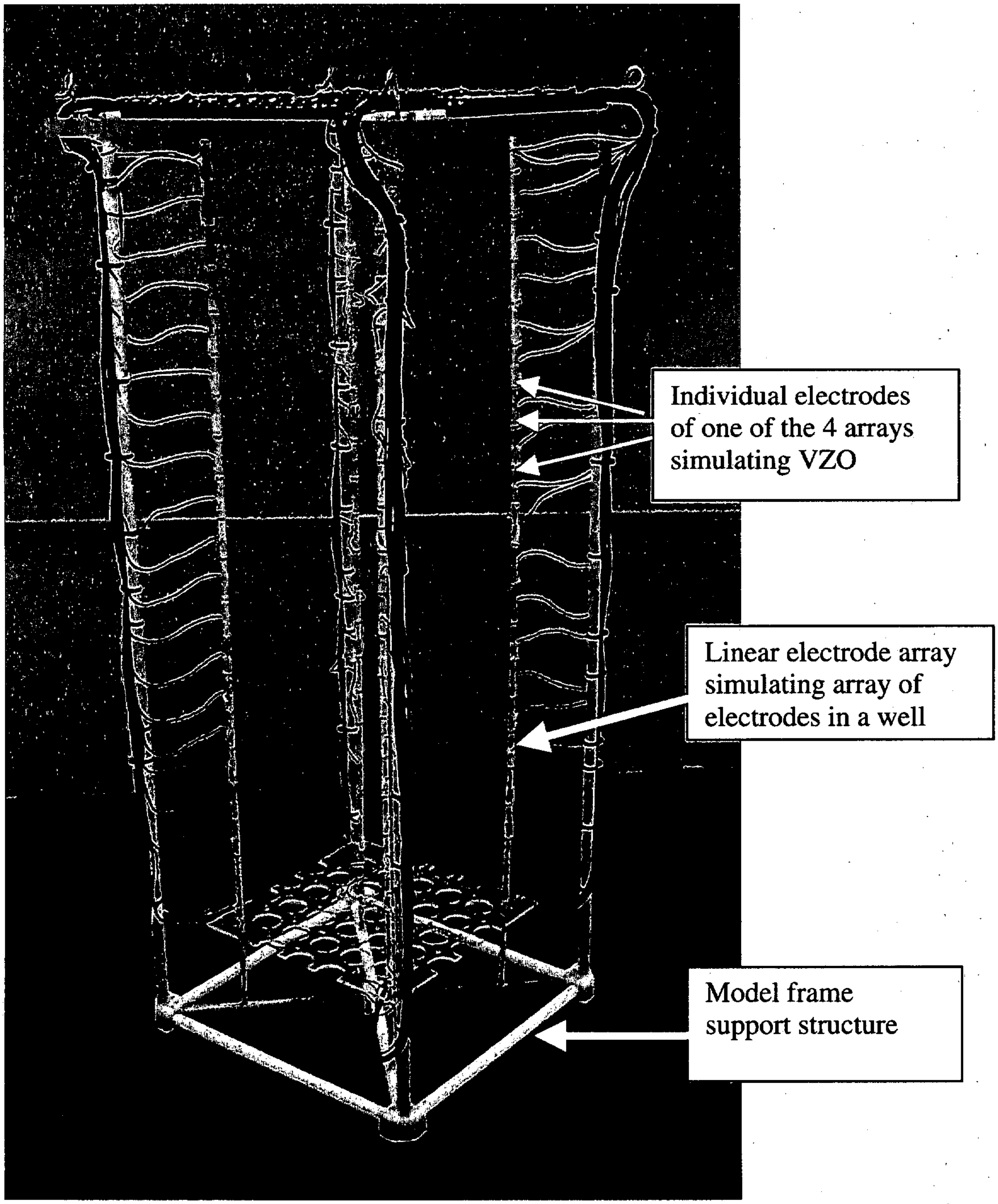


Figure 4.
Scale model ERT electrode array simulating 4 - well electrode array of the LLNL Vadose Zone Observatory. Additional electrodes on horizontal plexiglass frames at bottom and top allow imaging around objects in a manner similar to biomedical imaging. Of course, subsurface horizontal imaging beneath a target region is not possible for normal field situations. This feature will be utilized in future experiments conducted in collaboration with Rensselaer Polytechnic Institute.

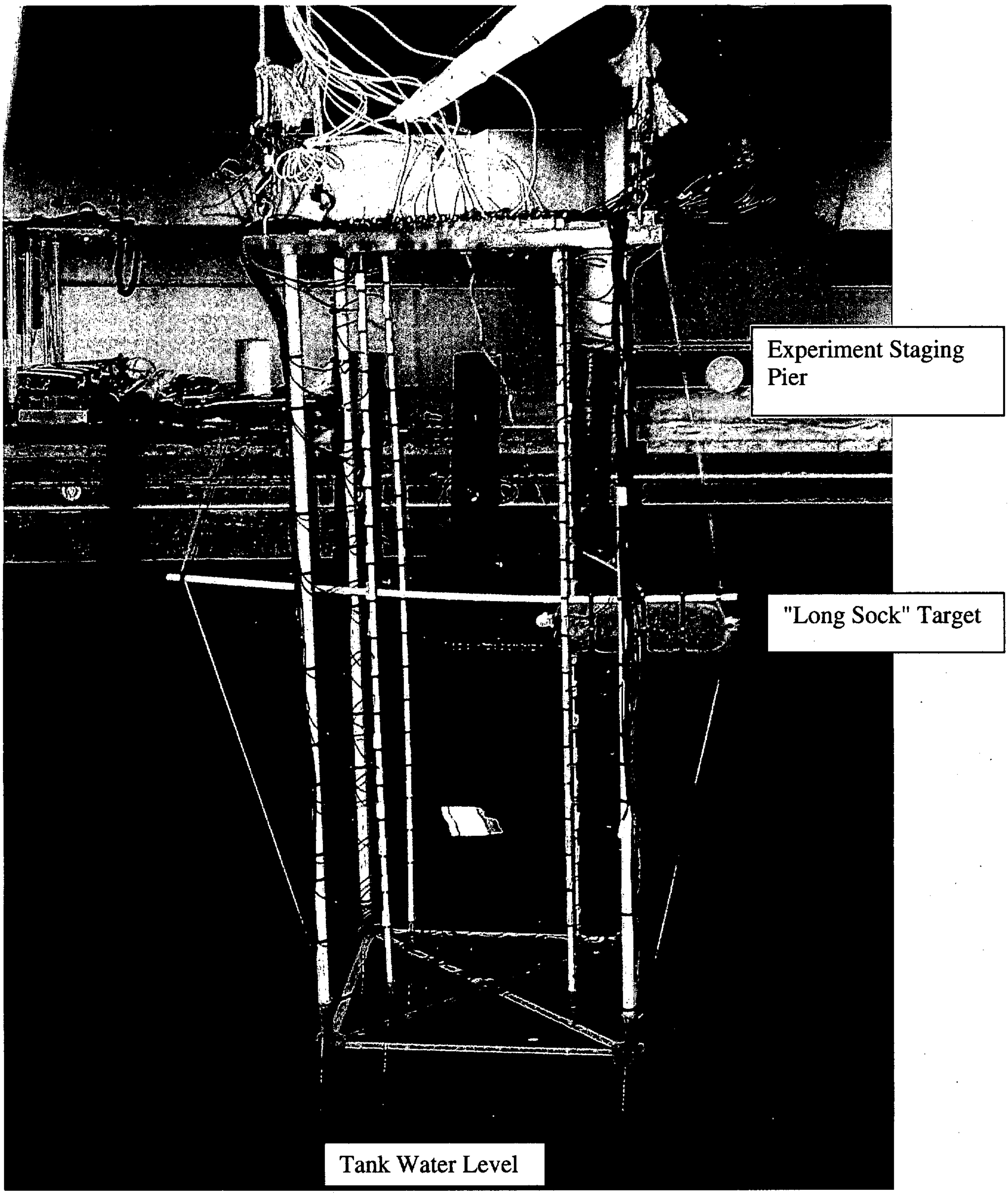


Figure 5
A porous conducting target simulating a hydrologic anomaly with slightly enhanced electric conductivity is mounted on the test frame before lowering in the water of the tank. As with other targets, the "long sock" is suspended at different locations on the frame to investigate the effect of location within the array domain on sensitivity, image size and distortion.

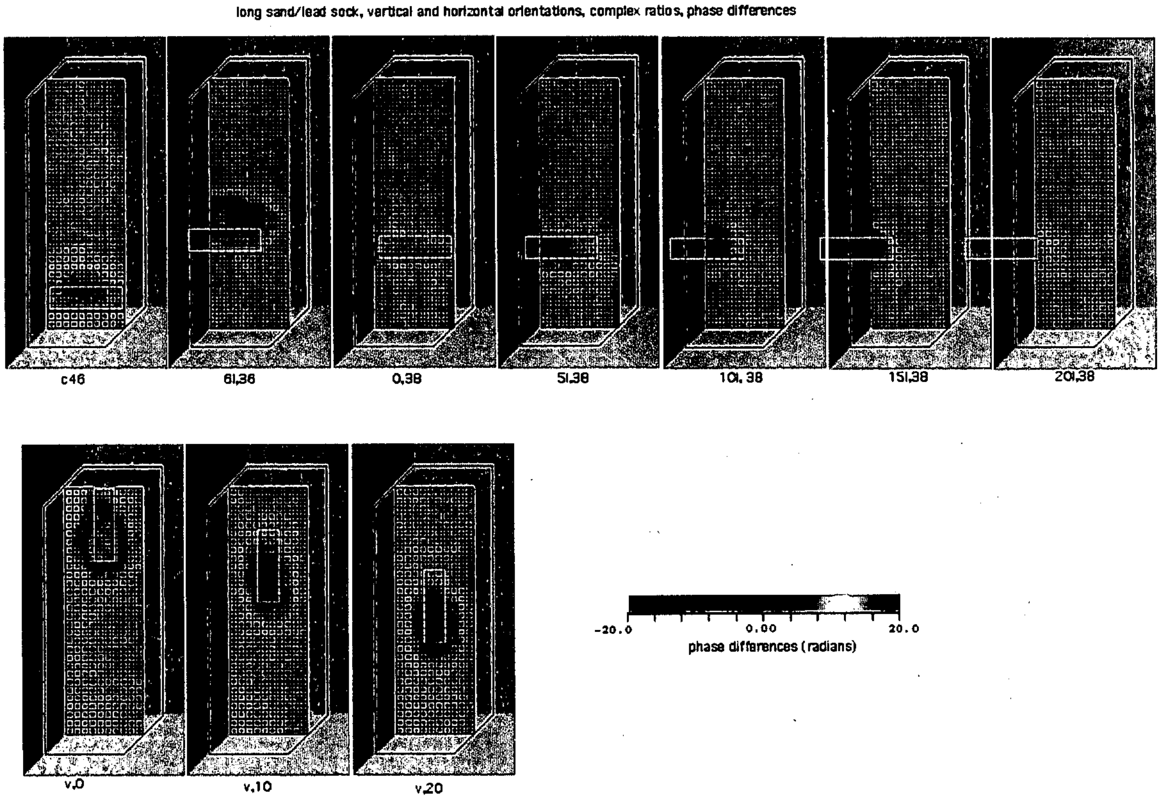


Figure 6
Imaging of the horizontal (top row) and vertical (bottom row) orientation of the long porous cylindrical sock target. Further analysis will be required to determine the degree to which image volume is conserved as well as the degree to which the center of mass is accurately imaged. This result is for the phase variation (imaginary part of complex resistivity) alone. Registration error in locating physical target may cause the apparent misalignment between ERT image and actual target represented here as a rectangle.

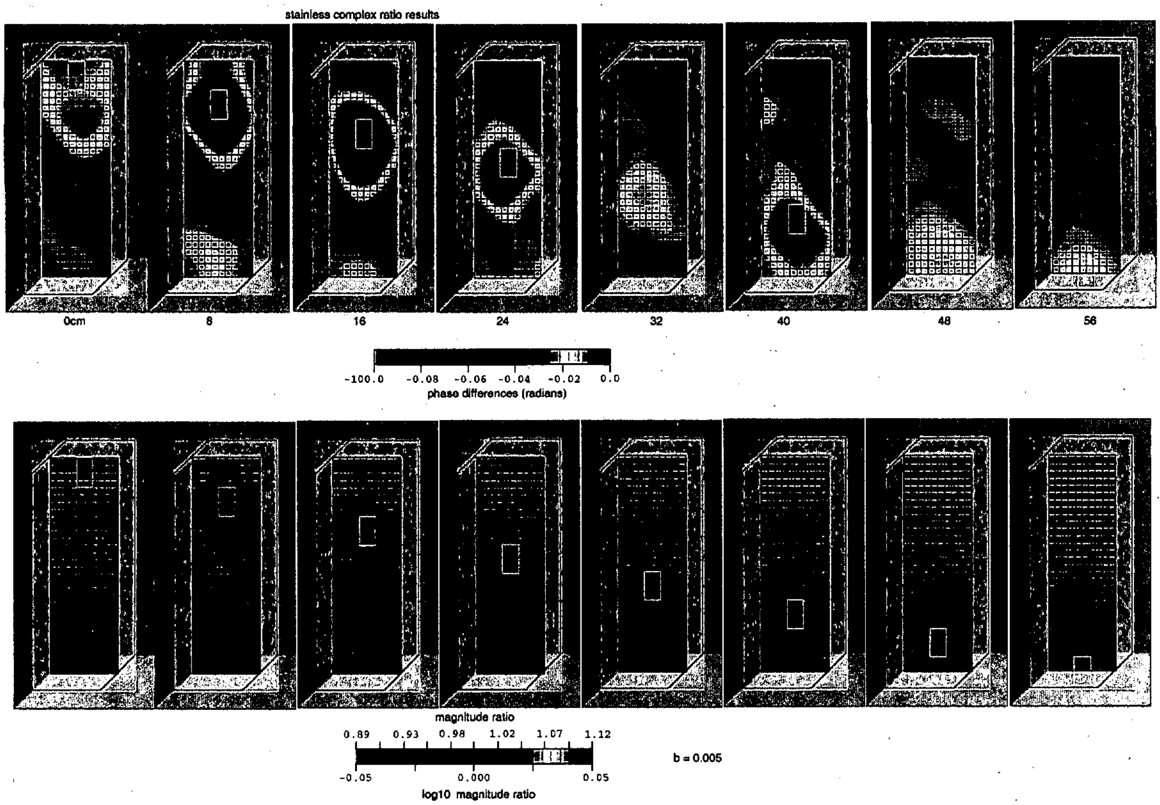


Figure 7

A high-conductivity contrast case was considered by imaging a machined stainless steel cylinder at different locations. Here the complex resistivity was broken into its phase and magnitude components. Even though the alternating current phase changes tend to be small, they appear to give the best signal compared to the magnitude or ohmic resistance of the complex resistivity. These experiments also give us the opportunity to investigate when can be learned by separately evaluating both the real (ohmic resistance) and imaginary (phase) parts of the complex resistivity.

Appendix

Northeastern
U N I V E R S I T Y

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January 2, 2002

Dr. Rokaya Al-Ayat
Director
Laboratory Science and Technology Office (L-003)
Lawrence Livermore National Laboratory
P.O. Box 808
Livermore, CA 94551-0808

Dear Dr. Al-Ayat:

I am writing to you to express my appreciation for Lawrence Livermore National Laboratory's current and continuing support of joint research projects with members of the NSF Center for Subsurface Sensing and Imaging Systems (CenSSIS). Recently, LLNL provided LDRD funding for Charles Carrigan to conduct a study entitled *"A Laboratory Approach to Relating Complex Resistivity Observations to Flow and Transport in Saturated and Unsaturated Hydrologic Regimes"* and for Sean Lehman to develop "Radial Reflection Diffraction Tomography" for the purposes of improving the current state of the art in intravascular ultrasound. Charles' project was aimed at developing a research program with CenSSIS researchers at the Rensselaer Polytechnic Institute (RPI), and brought together researchers with biomedical (RPI) and geophysical (LLNL) backgrounds to investigate new techniques for doing subsurface imaging of contaminant transport using electrical impedance methods. The commitment by your LDRD program to this work and particularly strong support in the Geosciences and Environmental Technologies Division at LLNL were undoubtedly important in obtaining three years of follow-on funding through the DOE Office of Basic Energy Sciences for a joint project that involves LLNL researchers, RPI faculty and graduate students. The intravascular ultrasound project ties together researchers from LLNL, Northeastern University, Boston University and the Massachusetts General Hospital with the goal of developing a tool to aid physicians in identifying potentially life threatening arterial plaque. Such projects that include researchers from diverse backgrounds fall very much in line with our Center's driving philosophy.

In 2000, CenSSIS officially became an NSF Engineering Research Center. This new organization brings together four universities, nationally recognized research organizations and more than twenty-five industrial partners to break new ground in remote image sensing to enhance research progress in biomedicine, geophysics, oceanography and materials science. CenSSIS is designed to systematically identify barriers that need to be overcome to reach breakthroughs in image sensing. As a generator for synergy, the ultimate product from CenSSIS is achieving similar solutions for diverse problems through information sharing with all parties benefiting.

I hope that this work will turn out to be highly productive for both Lawrence Livermore and its CenSISS collaborators. I look forward to having your lab as a continuing active partner in pursuing innovative solutions to significant problems in subsurface imaging.

Yours Sincerely,

Michael B. Silevitch
Director

CC: Ken Jackson, L-203
Norm Burkhard, L-221
Andrew U. Hazi, L-003
Donald J. Meeker, L-119
Harry E. Martz, L-151