Project Report on
Surface and Borehole Electromagnetic Imaging of Conducting Contaminant Plumes

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Abstract

Electromagnetic induction tomography is a promising new tool for imaging electrical conductivity variations in the earth. The EM source field is produced by induction coil (magnetic dipole) transmitters deployed at the surface or in boreholes. Vertical and horizontal component magnetic field detectors are deployed in other boreholes or on the surface. Sources and receivers are typically deployed in a configuration surrounding the region of interest. The goal of this procedure is to image electrical conductivity variations in the earth, much as x-ray tomography is used to image density variations through cross-sections of the body. Although such EM field techniques have been developed and applied, the algorithms for inverting the magnetic data to produce the desired images of electrical conductivity have not kept pace. One of the main reasons for the lag in the algorithm development has been the fact that the magnetic induction problem is inherently three dimensional: other imaging methods such as x-ray and seismic can make use of two-dimensional approximations that are not too far from reality, but we do not have this luxury in EM induction tomography. In addition, previous field experiments were conducted at controlled test sites that typically do not have much external noise or extensive surface clutter problems often associated with environmental sites. To use the same field techniques in environments more typical of cleanup sites requires a new set of data processing tools to remove the effects of both noise and clutter. The goal of this project is to join theory and experiment to produce enhanced images of electrically conducting fluids underground, allowing better localization of contaminants and improved planning strategies for the subsequent remediation efforts. After explaining the physical context in more detail, this report will summarize the progress made in the first year of this project: (1) on code development and (2) on field tests of these methods. We conclude with a brief statement of the research directions for the second year of the project.
1 Introduction to the Physical Problem

Electromagnetic induction tomography is a promising new tool for imaging electrical conductivity variations in the earth (Wilt et al., 1995a,b). The source field is a magnetic field generated by currents in wire coils. This source field is normally produced in one borehole, while the received signals are the measured small changes in magnetic field in another, distant ‘borehole; however, the method may also be used successfully in combination with surface sources and receivers. The goal of this procedure is to image electrical conductivity variations in the earth, much as x-ray tomography is used to image density variations through cross-sections of the body. Although field techniques have been developed and applied to collection of such EM data, the algorithms for inverting the magnetic data to produce the desired images of electrical conductivity have not kept pace. The current state of the art in electromagnetic data inversion (Alumbaugh and Morrison, 1995a,b) is based on the Born/Rytov approximation (requiring a low contrast assumption), even though it is known that conductivity variations range over several orders of magnitude and therefore require nonlinear analysis. The goal of this project is therefore to join theory and experiment to produce enhanced images of electrically conducting fluids underground, allowing better localization of contaminants and improved planning strategies for the subsequent remediation efforts.

Electromagnetic induction logging has long been used in the petroleum and environmental business to measure the electrical conductivity in the region immediately surrounding the borehole. This data, which is used to estimate pore fluid saturations near the well, is very sensitive to variations in rock pore fluid. Mapping surface variation of conductivity has also been found to be a very sensitive indicator of zones of higher salinity and acidity in many shallow environmental studies.

Recent research at LLNL (Newmark and Wilt, 1992; Wilt and Schenkel, 1992; Tseng et al., 1995; Berryman, 1997) has developed instrumentation and software to deploy EM induction technology in crosshole and surface-to-borehole configurations, thereby extending the conductivity information to the region between boreholes. This results in a determination of subsurface conductivity at a much higher resolution than can be achieved with surface techniques and much greater penetration than can be achieved with radar technology.
Although other technologies such as ERT (Berryman and Kohn, 1990; Dailey et al., 1992; Ramirez et al., 1993; Borcea, 1996; Borcea et al., 1996) can produce electrical conductivity images at a useful spatial scale, the advantage of the electromagnetic induction technology is that we can make use of existing monitoring wells and the surface to do imaging. Since signals are transmitted and received inductively, we do not need to make ground contact (no ground penetrating electrodes); the technology is therefore relatively noninvasive. There is also the important potential advantage that multiple frequencies can be employed to improve the imaging capability for electromagnetic induction tomography; this feature is simply not available with ERT imaging since the inversion methods used are inherently based on the DC (zero frequency) limit of the pertinent equations.

We have had good success deploying the EM induction technology in petroleum applications for field characterization and steam flood monitoring, but it has yet to be used in noisy urban areas where we are often unable to drill holes or do anything invasive. The targets for imaging in environmental problems are significantly more variable than in the petroleum production environment, ranging from highly resistive DNAPLs and petroleum products to highly conducting acidic brines.

In this report, we summarize the progress made in the first year of this project: (1) on code development and (2) on field tests of these methods. We conclude with a brief statement of the research directions for the second year of the project.

2 Progress in Code Development

The summary presented in this section describes collaborative work done by Nathan J. Champagne II, J. Brian Grant, Robert M. Sharpe, and H. Michael Buettner, all of the Lawrence Livermore National Laboratory.

Since the transmitters in our field experiments are induction coils with alternating current at a fixed frequency (typically in the range 1-10 kHz), our basic numerical problem is to solve Maxwell’s equations in the frequency domain. Because of the practical frequency range (< 1 MHz), it is adequate to ignore displacement currents in formulation as is typically done by other researchers, but it is not essential to do so in the particular implementation that we have chosen. We have used the finite-difference frequency-domain formulation of Beilnhooff et al. (1992) and the anisotropic PML (perfectly matched layer) approach (Berenger, 1994) to boundary conditions of Wu et al. (1997) to deal with the fact that the computations must be done in a finite domain even though the real problem is effectively of infinite domain. The resulting formulas for the forward solver reduce to a problem of the form

$$A\mathbf{x} = \mathbf{y},$$

(1)

where $A$ is a non-Hermitian matrix with real values off the diagonal and complex values along its diagonal (Smith, 1996a,b). The matrix $A$ may be either symmetric or nonsymmetric depending on details of the boundary conditions chosen (i.e., the particular PML used in the application). Equation (1) must be solved for the vector $\mathbf{x}$ (which represents field quantities such as electric and magnetic fields) with the vector $\mathbf{y}$ determined by the boundary conditions and transmitter location. There are many choices of forward solver for this system [see for example Saad (1996)], but not many of these have been thoroughly tested for the type of matrix encountered in our
problem. We found the stability characteristics of the standard Bi-CG algorithm for solving (1) to be quite inadequate (in terms of reliability and uniform accuracy) for this application and have chosen to use an alternative developed by van der Vorst (1992) for such situations called Bi-CGSTAB. We have found the stability characteristics of this solver to be entirely adequate for our application.

Considerable effort was devoted to finding good test cases for validating our new 3-D EM code. The Proceedings of the International Symposium of Three-Dimensional Electromagnetics which took place on October 4-6, 1995 at Schlumberger-Doll Research, contained a useful test problem in the contribution by Zhdanov and Feng (1995) in which a 20m x 10m x 10m conducting body is buried in a resistive half-space and excited by a wire loop transmitter. Our new code produced good agreement with the results of Zhdanov and Feng, and also with that from an older code, EM3d, from the University of Utah.

To demonstrate further the accuracy of the new code, we have tested various cases against results found in the literature. One example is for receivers down a borehole in a layered medium with air above the free surface. a 60m thick layer with \( \sigma = 0.3 \) S/m, a 25m thick layer with \( u = 0.016 \) S/m, and a 60m layer with \( \sigma = 0.2 \) S/m at the bottom of the model, with appropriately designed PML absorbing layers on all six sides of the domain. Relative permittivity of all three earth layers is constant and assumed to be \( \varepsilon_r = 10.0 \). The frequency of the excitation is \( f = 1 \) kHz with the transmitter located at the free surface with an offset of 5m from the borehole. The finite difference representation was chosen so the unit spacing in the earth model was 2.5m, with 50 cells x 50 cells in the \( xy \) direction, and 10 layers of PML on all four sides. In the vertical direction, there were 68 cells in the earth model, 10 cells in the air above the free surface, and 10 more cells above and below for the PML layers. All PML cells are 10m thick in the directions away from the earth model. The overall problem is then approximately \( 70 \times 70 \times 100 \approx 500,000 \) cells. The computations were performed on a DEC Alpha 8400 Model 5/4400, and required approximately 2 hours of CPU time. including about 2000 iterations to achieve the desired convergence. This computation was serial and required about 500 MB of memory. In Fig. 1 the results of the code calculations for the magnetic field magnitude and phase are compared to results for the same model obtained using the code EM1D based on a semianalytical formula for such layered models and developed by Ki-Ha Lee at LBNL. The observed agreement is excellent.

The new code is written in Fortran 90 and is designed to be easily parallelizable, but we have not yet tested this feature of the code. We anticipate an improvement in execution time when the parallel features are invoked, but otherwise we expect the performance to be the same on the same computer platform.

3 Progress on Field Tests of the Methods

The summary presented in this section describes collaborative work done by H. Michael Buettnner, Clifford Shenkel, and Michael J. Wilt.

3.1 Experimental, field, and related work

Planning took place to improve the EM data acquisition system. Improvements include: 1) additional data channels, 2) faster, more reliable software, 3) purchase and testing of 3 new
magnetometers for hole to surface imaging work, 4) securing a larger, newer, more reliable, safer data acquisition vehicle, and 5) a larger, newer, more reliable, safer boom/logging truck. The new system should allow us to collect better quality data more rapidly and reliably. Items 1, 3, 4, and 5 have been accomplished.

3.2 Experimental work at Lost Hills, CA

During the week of April 7, we collected borehole to surface EM data for a shallow steam injection which is underway at Mobil Oil’s Lost Hills-3 field. This is an interesting case because it can be viewed as an analog of a shallow environmental remediation using steam injection. Surface magnetic field data (vertical and radial fields, magnitude and phase) were collected at 18 receiver stations along two profiles which ran radially from the EM transmitter well from 5 m to 120 m. The data at each surface station were collected while the EM transmitter was raised slowly from a depth of 120 m to a final depth of 20 m. As part of this experiment, a calibration of the EM transmitter was also performed.

The data from this experiment have not been analyzed as yet, primarily because good interpretation tools are not available. Some simple 1-D modeling was done to confirm that the expected conductivity change in the steam zone should produce an anomaly large enough to detect in the measured data when comparing the pre-steam to the post-steam conditions.

During this effort, we worked on the problem of removing cultural effects (e.g., fences, pipes, etc.) from EM data. This involved a survey of the literature and discussions with M. Wilt and W. Daily. The only approach found thus far involves spatial filtering of the raw magnetic field data. That is, the rapid spatial variations need to be filtered out before interpretation begins.

4 Directions of Research in the Second Year of the Project

We will continue to test and improve the forward modeling capability developed in the first year of the project. At the same time a new approach to the inverse problem of electromagnetics is
being developed based on the so-called “adjoint technique.” This method has the very useful property that the inverse problem can be solved approximately by making two uses of the same forward modeling code we have already developed. The updates to the electrical conductivity will be obtained by first making one pass through the code using the latest best guess of the nature of the conducting medium, and then another pass with the adjoint operator (which for this problem is just’ the conjugate transpose of the operator $A$). Then the results of the two calculations are combined to determine the update to the original conductivity model.

Fields tests are planned for the second year as well. There is one field site at present which may present a good opportunity for field testing our system. That site is the Southern California Edison pole yard at Visalia, CA, which is contaminated with creosote. The site is currently under steam remediation and is being monitored using ERT (electrical resistance tomography). Other sites may become available as well.

EM induction data were collected at the LLNL main site recently by a group from UC Berkeley, and these data are available to us. This is not an active remediation site, but it does have some of the elements of interest to us. For example, it has some organic contamination, soils typical of the Western United States, and monitoring wells for both EM induction and ERT.

We would also like to conduct a calibration for our EM transmitter coils at a highly-resistive site if such a site can be found where the experiment can be done for a reasonable cost.

References


Berryman, J. G., 1997, Challenges for computational physics in underground imaging of electrically conducting contaminant plumes, invited talk P2.03 in special session on Geological Phenomena at the International Conference on Computational Physics, American Physical Society, Division of Computational Physics, Santa Cruz, California, August 25-29, 1997.


