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Surface and Borehole Electromagnetic Imaging of Conducting Contaminant Plumes

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Research Objective

Electromagnetic induction tomography is a promising new tool for imaging electrical conductivity variations in the earth. 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 is based on the Born/Rytov approximation (requiring a low contrast assumption), or extensions. However, it is known that conductivity variations in fact 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.

Research Progress and Implications

Code Development

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 ange (< 1 MHz), it is adequate to ignore displacement currents in the formulation as is ypically done by other researchers, but it is not essential to do so in the particular mplementation that we have chosen. We have used the finite-difference frequency-domain formulation and an anisotropic PML (perfectly matched layer) approach to oundary conditions to deal with the fact that the computations must be done in a finite omain even though the real problem is effectively of infinite domain. The resulting ormulas for the forward solver reduce to a problem of the form Ax = y, where A is a non- ermitian matrix with real values off the diagonal. The matrix A may be either symmetric r nonsymmetric depending on details of the boundary conditions chosen (i.e., the articular PML used in the application), but in our implementations we always try to make hoices resulting in symmetric matrices. The equation Ax=y must be solved for the vector which represents field quantities such as electric and magnetic fields) with the data vector etermined by the boundary conditions and transmitter location. There are many choices of forward solver for this system, but few of these have been thoroughly tested for the type of matrix encountered in our problem. We found the stability characteristics of the frequently used Bi-CG algorithm for solving Ax=y to be quite inadequate (in terms of both reliability and uniform accuracy) for our application and have chosen instead to use an alternative developed for such situations called Bi-CGSTAB. We have found the stability characteristics of the new 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. 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 conductivity 0.3 S/m, a 25m thick layer with conductivity 0.016 S/m, and a 60m layer with conductivity

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 equal 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 by 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 70x70x100 ~= 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. The results of the code calculations for the magnetic field magnitude and phase have been compared to results for the same model obtained using the code EM1D based on a semianalytical formula for such layered models. The observed agreement is excellent. Further tests in two and three dimensions have been performed or are in progress.

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 characteristic that the inverse problem can be solved approximately by making two uses of the same forward odeling code that we have already developed. The updates to the electrical conductivity are obtained by first making one pass through the code using the latest best guess of the characteristics of the conducting medium. Then another pass is made with the adjoint operator (which for this problem is just the conjugate transpose of the operator A, and therefore for symmetric A changes only the sign of the imaginary part of the diagonal elements). Then the results of the two calculations are combined to determine the update to the original conductivity model.

Field Work and Data Interpretation

The improvements to the data acquisition system have been planned and implemented. improvements included: (1) additional data channels, (2) faster, more reliable software, (3) purchase and testing of three new magnetomaters for borehole and surface imaging work, and (4) securing a larger, newer, more reliable, safer data acquisition vehicle, and (5) a larger, newer, more reliable, safer boom/logging truck. All these improvements are now essentially complete and the system was successfully field tested in April, 1998, during a cross-borehole data collection at Lost Hills, CA, an active oil field owned by Bakersfield Energy Company. The system worked well, and only minor changes should be necessary from now on.

The Lost Hills experiment had 500 transmitter positions in the borehole ranging in depth from 20 to 120 m. Transmitter polarization in the borehole was always vertical. (The data were later decimated to only 100 transmitter positions to eliminate redundant data.)

The receivers on the surface were placed at 18 locations ranging from 5 to 120 m in steps of either 5m (out to 60m) or 10m (beyond 60m) from the transmitter borehole. Two nearly orthogonal surface survey lines of this type were used, and both vertical and radial polarization data were collected for each line. Total data collection after decimation was therefore 18x2x2x100 = 7200 measurements. These field data from Lost Hills, CA, have een reduced and are currently being interpreted, and prepared for use in our inversion code.

Planned Activities

Code development is the main focus of the project in the near term as we need the inversion code to analyze the data already collected as well as for any new data we will collect. Further fields tests are planned. One field site which may present a good opportunity for field testing our system is the Southern California Edison pole yard at Visalia, CA, which is contaminated with creosote. This site is currently under steam remediation and is also being monitored using ERT (electrical resistance tomography). Other opportunities for field testing are also being explored. Two papers are currently in preparation, one on the computational aspects of forward modeling and another on the theoretical and computational aspects of the inversion methods. A third paper summarizing our field experience will follow.

Other Access To Information

For more information on this project, please contact:

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