EMSP Project Summary/Progress Report for FY98-FY00 for Project #55011

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. Prior to this project, the state of the art in electromagnetic data inversion was based on the Born 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 has therefore been 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. The resulting field system can, after some more required work on calibration and reliability, be applied directly to EM characterization and remediation problems.

Research Progress and Implications

Project #55011 consisted of three major activities, with the major goal of developing EMIT into a mature field tool for environmental imaging applications:
(1) Development of an electromagnetic forward modeling capability in the appropriate frequency range (1-20 kHz) at LLNL for the first time.
(2) Development of a new electromagnetic data inversion method at LLNL and Stanford for the first time.
(3) Further development and upgrading of the field capabilities for EMIT, as well as use of these capabilities at an appropriately chosen field site.

(1) Forward Modeling Capability

Our forward modeling efforts are summarized in papers by Champagne et al. (1999; 2000) and Berryman {\em et al.} (1999). The resulting code is a 3D finite-difference Fourier-domain code that has been extensively tested against analytical results and results obtained from other codes. We call the code FDFD because of its finite-difference Fourier-domain character. As will be mentioned again in the next subsection, our forward modeling capability had special requirements, because it needed not only to produce the forward predictions of electrical and magnetic fields for given source configuration, but also to provide a simple means of computing the adjoint operator that was to be used in our new inversion method. This requirement was met by the code FDFD summarized in the papers already mentioned. The forward modeling capability development was one of the major achievements of the first two years of the project.

(2) EMIT Data Inversion Methods

Our most recent work on data inversion has developed an ``adjoint method'' for inverting these data (Champagne et al., 1999; 2000; Berryman et al., 1999; Dorn et al., 1999), thereby allowing higher resolution and higher contrast images than were previously possible. The paper by Dorn et al.(1999), which was recently published in Inverse Problems summarizes a major new direction for research on EMIT data inversion problems of the type required for this project. The forward modeling efforts of Champagne et al. (1999; 2000) and Berryman et al. (1999) were critical for the development of the adjoint method because the adjoint method requires a method of computing the operator adjoint. Our forward modeling code was designed to make this set no harder than that of computing the forward result for the operator. The adjoint method of data inversion was one of the major achievements of the second and third years of the project.

We also have produced related work on electrical resistance/impedance imaging methods for high contrast media (Borcea et al., 1996; 1999) and on approaches to the analysis of both our own methods and those of others to quantify the attainable resolution in each situation (Berryman, 2000a,b).

(3) Field Work and Data Interpretation

Field equipment was acquired and assembled into a coherent data acquisition system for use by LLNL personnel for the first time. Some of our equipment was used by Berkeley students at the LLNL ACI site in both crosswell and surface-to-borehole tests and this project shared that data and the analysis of the data.

One field experiment was performed at Lost Hills, CA, in April, 1998, and the results were presented at SAGEEP by Buettner and Berryman (1999). At the Lost Hills site, steam had been injected into upper, middle, and lower zones of the Tulare formation since 1991 using injector 5035. More recently injector 5035 was refractured with steam, and service well O35 was completed as an injector for the middle and lower zones in order to increase the injection rate. The object of our monitoring was the shallow zone which extends from about 60 m to 85 m depth. Further details about the field site and the results may be found in the paper by Buettner and Berryman (1999) and in its references. The data acquisition system integration and the field test were two of the major achievements of the first and second years of the project. Analysis of the field data using the new inversion methods will be one of the first items to be addressed in the renewal project if the renewal proposal is successful.

Planned Activities

The project was completed, including a no cost extension of three months, at the end of December, 1999, so no further work is planned or contemplated at this time until new funding arrives. A renewal proposal was submitted March 15, 2000. If the proposal is successful, the renewal project will lead to a well tested and calibrated field system and imaging tool that can subsequently be applied directly to EM characterization and remediation problems.

Publications

Berryman, J. G., Analysis of approximate inverses in tomography. I. Resolution analysis of common inverses, Optimization and Engineering, to appear in Volume 1 No. 1, 2000a.

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Borcea, L., J. G. Berryman, and G. C. Papanicolaou, High contrast impedance tomography, Inverse Problems, 12, 835-858, 1996.

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Champagne, N. J., II, J. G. Berryman, H. M. Buettner, J. B. Grant, and R. M. Sharpe, A finite-difference frequency-domain code for electromagnetic induction tomography, in Proceedings of SAGEEP, Oakland, CA, March 14--18, 1999, pp. 931--940.

Champagne, N. J., II, J. G. Berryman, H. M. Buettner, FDFD: A 3D finite-difference frequency-domain code for electromagnetic induction tomography, submitted to J. Computational Phys., currently under review for publication in 2000.

Dorn, O., H. Bertete-Aguirre, J. G. Berryman, and G. C. Papanicolaou, A nonlinear inversion method for 3D-electromagnetic imaging using adjoint fields, Inverse Problems, 15, 1523-1558, 1999.

Information Access

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