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Fast Two-Dimensional Forward and Inversion Algorithms for Interpreting Marine CSEM Data

D.L. Alumbaugh, A. Abubakar, V. Druskin, T. Habashy, and A. Zerili, Schlumberger; L. Knizhnerman, Central of Geophysical Expedition; and G.M. Hoversten, Lawrence Berkeley Natl. Laboratory

Abstract

We present two-dimensional forward and inversion algorithms for the interpretation of marine controlled-source electromagnetic data. The forward algorithm employs a staggered-grid finite difference solution to the total-electric-field Helmholtz equation. Quick solution times are achieved through a) an optimal grid technique that extends the boundaries of the mesh outward from the region of interest using a minimal number of nodes, and b) a direct matrix solution technique that allows for the simultaneous solution for all sources. In addition an anisotropic conductivity averaging formula is employed to upscale models with very fine details to a coarser computational mesh. Simulation of simple models show the accuracy to be within one percent for amplitude and one degree phase as long as there are at least six to ten finite-difference-node-points between the source and receiver. The inversion is accomplished via a constrained Gauss-Newton technique where the model parameters are forced to lie within upper and lower bounds via a nonlinear transformation procedure. The Jacobian is computed using an adjoint method where all of the forward solutions required for computation of both the data misfit as well as the Jacobian matrix are achieved through one run of the forward solution. Employing a line search method enforces reduction of the cost function at each iteration. To improve the conditioning of the inversion problem, we use one of two different model-structural constraints. The first is a traditional $L2$-norm regularization scheme, which provides for a smooth solution. The second is the so-called weighted $L2$-norm constraint (or L1-like norm) that can provide a sharp reconstructed image. The trade-off parameter which provides the relative weighting between the data and the model-constraint part of the cost function is determined automatically to enhance the robustness of the method. The performance of the algorithm is demonstrated using two different models; a simple 2D model with an 8km wide, 100m thick reservoir unit, and a more complicated 3D example simulating complex channel-structures at depth. These examples are further employed to demonstrate the degradation caused by increasing data noise, and the image enhancement that results by using multiple electromagnetic field components.

Introduction

Marine controlled source electromagnetic (CSEM) methods have recently received increased attention as a hydrocarbon exploration tool [1,2,3,4,5]. The interest results from the technique's ability to directly detect the presence of thin hydrocarbon bearing layers at depth. Initially, data were analyzed by plotting electric field amplitude versus source-receiver offset, and then normalizing the data that were acquired over a possible hydrocarbon prospect by data measured over a similar non-hydrocarbon bearing area [1,2]. Because the presence of hydrocarbons at depth increases the amplitude of the measured electric field, the normalized value will be greater than unity for areas containing resistive anomalies at depth, and unity or less for non-hydrocarbon bearing areas. Although this method will provide information of the presence of the hydrocarbon, as well as some information about the horizontal location and extent of the reservoir, it is difficult to discern depth and true geometry of the oil/gas bearing units from normalized curves by themselves.

To provide this additional information, researchers are increasingly turning to modeling, imaging, and inversion techniques [e.g. 6,7]. For producing approximate images of subsurface conductivity structure, one can employ fast imaging techniques such as the migration wave-field imaging approaches [e.g. 8,9,10]. Though very quick, these approaches generally provide low resolution images that can be difficult to interpret in terms of true conductivity structure. The other extreme involves rigorous forward and inversion algorithms such as the 2D scheme employed in [5] and the 3D algorithm developed by [11]. These tend to be computationally expensive due to the forward modeling schemes that are employed as the driver which involve the solution via iterative sparse matrix solution techniques. These methods generally require that only one source can be solved for at a time. In any event, a 2D inversion may take hours to days for an inversion on a standard serial computer, while the 3D inversion may