A rigorous nonlinear inversion algorithm for interpreting deep geophysical electromagnetic measurements

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Electromagnetic (EM) methods are essential tools for the appraisal of a reservoir because of their sensitivity to the resistivity which is a function of the fluid saturation. One of the traditional EM techniques for well logging is the induction single-well measurement. This technique is employed to estimate near well-bore resistivity. It has a sensitivity of up to a few meters from the well and is a function of the separation between the transmitters and receivers as well as the frequency of operation. To reach deeper into the reservoir, a cross-well EM induction technology was developed. The system operates very similar to the single-well logging tool however with transmitters and receivers deployed in separate wells. During a cross-well survey the receivers are lowered into one well, initially to the bottom of the survey-depth interval. Then the transmitter is lowered into the second well and is moved to log the entire survey-depth interval. During logging the transmitter broadcasts EM signals at a number of pre-prescribed frequencies while at the receiver well these signals are recorded. After the transmitter run is completed the receiver array is moved to the next depth station in the survey interval and the process is then repeated until the entire depth interval has been covered. After the data set has been collected, an inversion process is applied to obtain the resistivity distribution between the wells.

This inverse process is one of the most challenging parts of the effort to make this cross-well technology work since it requires one to solve a nonlinear inverse scattering problem, which is usually ill-conditioned and non-unique. Moreover, when the number of the model parameters to be inverted is large, the inversion can be very time-consuming mainly due to the computation of the Jacobian matrix needed to construct the search direction. In order to carry out the inversion within a reasonable time, we employ a finite-difference code as a forward simulator. In this forward code the configuration is discretized using a small number of cells determined by the optimal grid technique. The resulting matrix representing the discretized forward problem has to be inverted in each inversion step. To invert it, we use a direct method that allows us to obtain the solution for all transmitters simultaneously. Furthermore, in order to be able to use the optimal grid without sacrificing accuracy we use an anisotropic material averaging formula. All these features help in reducing the computational time for constructing the Jacobian matrix and for calculating the data misfit. For the inversion method, we employ a constrained Gauss-Newton minimization scheme where the inverted model parameters are forced to lie within their physical bounds by using a nonlinear transformation procedure. We further enforce a reduction in the cost function after each iteration by employing a line search method. To improve on the conditioning of the inversion problem, we use two different regularizers. The first is a L2-norm regularizer, which allows a smooth solution. The second is the so-called weighted L2-norm regularizer, which can provide a sharper reconstructed image. The regularization parameter which provides the weighting between the data and the regularization part of the cost function is determined automatically to enhance the robustness of the method. In the presentation, we will present results from simulated data as well as from field measurements.