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Considerations about the Solution Space of a VTI Marine CSEM Inversion Problem Using Vertical Antennas

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SUMMARY

We exploit the randomness of a genetic inversion algorithm to map the global minimum of the solution space of Controlled-Source Electromagnetic inversion problems. In this study, we focus on the information content that vertical electric or magnetic receivers could add to solve for anisotropic conductivities of the subsurface. By analyzing the distribution of the found solutions by the genetic algorithm, we find that the vertical magnetic component adds complementary information to the horizontal components.

Introduction

Controlled-Source Electromagnetics (CSEM) as applied by the hydrocarbon industry uses very low frequencies (between approximately 0.1 and 10 Hz) to ensure that the signal penetrates to the required depth (Constable, 2010). At these frequencies, the electromagnetic field propagates diffusively, which makes a direct interpretation using "events" like in seismics impossible. Therefore, the common processing flow contains an inversion for the subsurface conductivity distribution (e.g., Christensen and Dodds, 2007; Key, 2009; Ray et al., 2013; Grayver et al., 2014).

In this study, we focus on frequency-domain marine CSEM. We use a genetic algorithm (for an introduction see Goldberg, 1989) to probe the solution space of CSEM inversion problems, which include vertical electric or vertical magnetic receivers. More details about the algorithm will be given in the next section. In an earlier study (Hunziker et al., 2014), where we have used the same approach, the solution space of a CSEM inversion problem was investigated using horizontal antenna's. We have found, that for an isotropic medium the electric field is sufficient to find the subsurface conductivity. However, for a vertical transverse isotropic (VTI) medium, which features different conductivities in the vertical and in the horizontal direction, the magnetic field is useful as well for finding a solution. Here, we aim to find out if incorporating vertical components further improves the solution in a VTI medium.

Method

A genetic algorithm mimics evolution theory to find the global minimum of a function. In our case, this function is a normalized least-squares misfit between modeled data and acquired data. Since this is a numerical study, the acquired data are simulated data. In this way, the algorithm is supposed to find the conductivity distribution of the subsurface that explains the data. The algorithm starts with a random set of solutions to the problem. The misfit of each solution gives the chance that a specific solution, which is encoded as a string of characters or binaries, may be selected for the next iteration. If a solution is selected, it may undergo the process of crossover or mutation. In crossover, the string encoding the solution is cut at a random location and the tail is exchanged with another selected solution. In this way, different parameters that have a small misfit are recombined. In mutation one random character of the string which encodes the selected solution is replaced by another random character. In this way, one of the parameters of a solution with a small misfit is altered. To ensure that the best solution of one iteration will not be lost in the next iteration, either through crossover or through mutation, a certain percentage of the best solutions is passed on to the next iteration also in unaltered form. This process is called eliting. A similar percentage of the population is replaced at every iteration with new random solutions. This process is called migration. The benefit of such a global inversion algorithm is, that it is able to jump out of a local minimum. The disadvantage is, that only small sets of parameters can be inverted for.

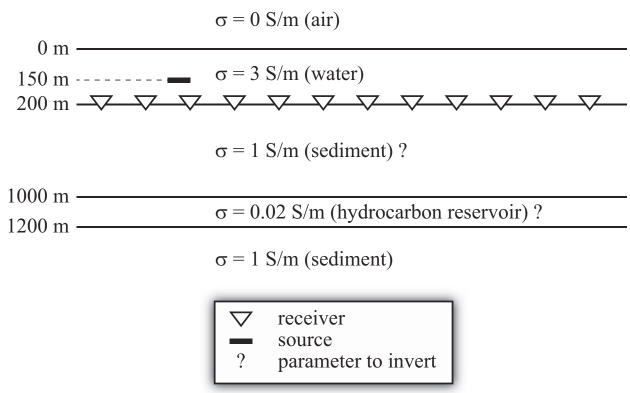

***Figure 1** Acquisition geometry and subsurface model. Taken from Hunziker et al. (2014).*

In this study, we exploit the randomness of this algorithm. Due to the random starting solutions and due to the randomness of the process itself, the algorithm rarely finds the exact same solution after different runs. However, we assume that almost all runs end up within the global minimum. Thus, plotting the solutions of several runs maps out the shape of the global minimum. We consider here a simple inversion problem with only four unknowns, but we assume that the conclusions taken from this simple problem are also valid for more realistic inversion problems with thousands of unknowns. In our experiment, each run starts with 150 random solutions, which are evolved over 100 iterations. For each experiment, we conduct 15 independent runs.

Results

The medium under consideration is depicted in Figure 1. It consists of a stack of layers. The inversion algorithm aims to find the vertical and horizontal conductivity, σ^V and σ^H, of the layers marked with a question mark. These are the overburden layer, which lies between the water and the reservoir, and the reservoir layer itself. The receivers are located at the ocean bottom (white triangles) and the source is 50 meters above the receivers (black bar). Although Figure 1 suggests a 2D setup, we actually implemented a 3D geometry with a grid of receivers instead of a line. To avoid a bias toward vertical or horizontal conductivity, the same value has been chosen for both, making the medium effectively isotropic. But the inversion is searching for vertical and horizontal conductivity, making it a VTI-algorithm.

In our previous work (Hunziker et al., 2014), which uses the same setup, we have shown that the horizontal components of the electric field are mainly sensitive to the horizontal conductivity in the overburden layer and to the vertical conductivity in the reservoir layer. Adding the horizontal magnetic components helps to estimate quite well the vertical conductivity of the overburden and improved also to a lesser extent the guess of the horizontal conductivity of the reservoir. Thus, as mentioned in the introduction, for an isotropic medium, the horizontal electric field alone contains sufficient information, but for a VTI-medium, the horizontal magnetic field adds valuable information to the inversion process.

In this study, we are interested in the question whether the vertical components add more valuable information to the inversion process. For all our experiments we used an inline oriented source only. As a first experiment, we would like to see, how well the different parameters are resolved if only vertical electric receivers or only vertical magnetic receivers are used. The results for the vertical electric receivers are shown in Figure 2a and 2b, while the results for the vertical magnetic receivers are shown in Figure 2c and 2d.

Using vertical electric receivers provides a good guess of the horizontal conductivity of the overburden layer (layer 1), and a somewhat less resolved guess of the vertical conductivity of the overburden layer. Judging from the color of the dots, which defines the value of the misfit function, the global minimum for the overburden layer is a sharp depression with respect to the horizontal conductivity and a rather broad depression in the direction of the vertical conductivity. The vertical conductivity of the reservoir layer (layer 2) is well resolved, while the horizontal conductivity is badly resolved. The color of the dots suggests a narrow valley of the solutionspace with respect to vertical conductivity. At the same time, the valley is very long with respect to horizontal conductivity.

The vertical magnetic receivers show a quite different picture. Although the horizontal conductivity of the overburden is resolved very well as was the case for the vertical electric receivers, the vertical conductivity is not resolved at all. However, most surprising are the results for the reservoir layer. While the vertical electric receivers were able to resolve the vertical conductivity, the vertical magnetic receivers are able to resolve the horizontal conductivity. The value of the misfit function seems to be primarily determined by the estimated conductivity for the reservoir layer, which forms a canyon parallel to the axis of the vertical conductivity.

The inversion results for the vertical magnetic receivers encourage to perform a joint inversion of the four horizontal components and the vertical magnetic component, because the latter could add information about the horizontal conductivity of the reservoir. The results of such an inversion are shown in Figure 3a for the overburden layer (layer 1) and in Figure 3b for the reservoir layer (layer 2). The estimate of the conductivities of the two layers does not change considerably compared with a joint inversion of the four horizontal electromagnetic components only (see Figure 3e and 3f of Hunziker et al. (2014)). Although

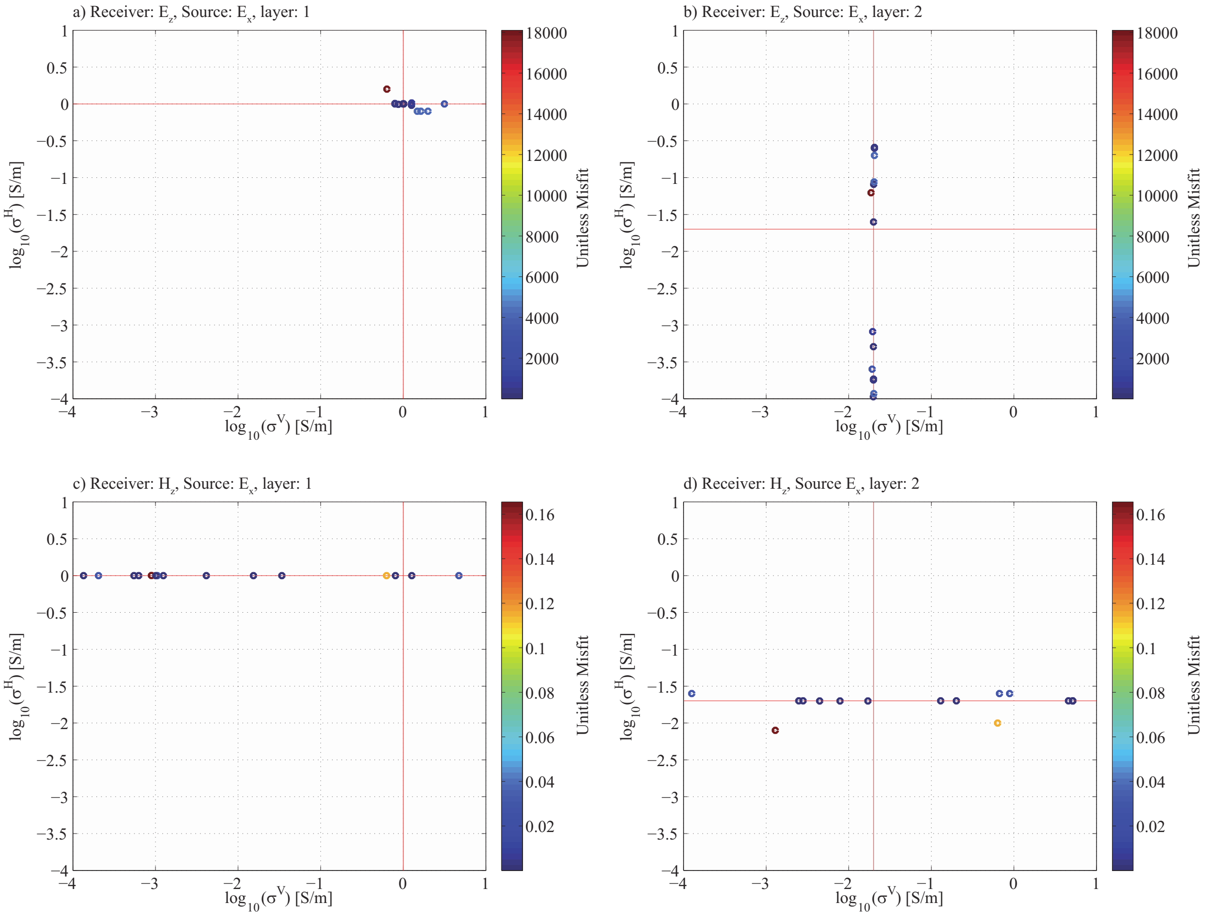

Figure 2 *Parameter space with found solutions (colored dots) and correct solution (red cross). Subfigures a) and b) show the solutions found for the overburden layer (layer 1) and for the reservoir layer (layer 2), respectively, using vertical electric receivers. Subfigures c) and d) show the same using vertical magnetic receivers. The color of the dots is the final misfit of the solution. The misfit is unitless because it has been normalized with the data. Note that the axes are logarithmic.*

the vertical magnetic component seems to provide information about the horizontal conductivity of the reservoir (Figure 2d), a joint inversion of the horizontal electromagnetic components together with the vertical magnetic component is not able to resolve the horizontal conductivity.

It seems that the vertical magnetic component does not have enough weight to influence the inversion process significantly. We therefore multiply the misfit of the vertical magnetic component with a weighting factor of 1000. The corresponding results are depicted in Figure 3c and 3d. The spread of the solution for the horizontal conductivity of the reservoir has now been reduced showing the influence of the vertical magnetic component. A further increase of the weight (not shown) leads to an increase of the spread of the vertical conductivity of the overburden layer. Thus, a joint inversion with appropriate weighting improves the result only in a limited manner.

Conclusions

In earlier work we have shown that the horizontal electric components provide enough information for inverting the data for an isotropic conductivity distribution of the subsurface. If the medium features VTI-anisotropy, adding the horizontal magnetic field improves the estimate of some of the parameters. Here, we have shown, that the vertical magnetic component is able to add additional complementary information to a VTI-inversion process. In a joint inversion using the four horizontal electromagnetic

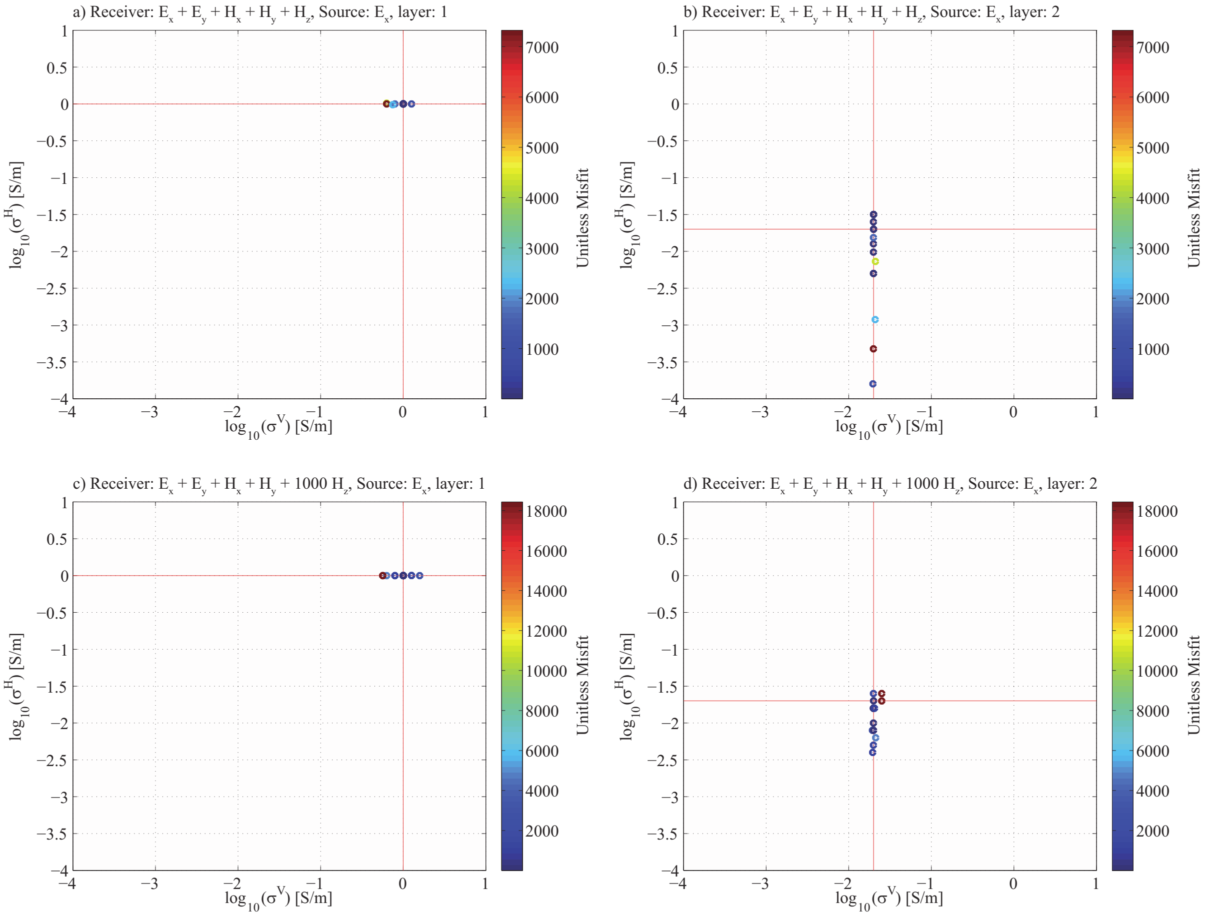

Figure 3 Joint inversion of the four horizontal electromagnetic components and the vertical magnetic component. Subfigures a) and b) show solutions for the overburden layer (layer 1) and for the reservoir layer (layer 2) giving the same weight to all five datasets. Subfigures c) and d) show the same giving a weight of 1000 to the vertical magnetic component. Otherwise the same as Figure 2.

components plus the vertical magnetic component, weighting of the vertical magnetic component becomes important.

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