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SVD analysis of the electric and magnetic fields for the MCSEM data

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Abstract Summary

This paper deals with geophysical inversion in the context of the MCSEM (Marine Controlled-Source Electromagnetic) method, which is widely used in hydrocarbon prospecting in marine environments. Given the high computational cost of inversion, we propose the use of singular value decomposition (SVD) to evaluate the quality of the data and the feasibility of inversion by analyzing the null space of the sensitivity matrix. Unlike most studies that focus on the electrical response, this research highlights the potential of the magnetic field, which is less explored but is sensitive to different physical properties of the medium, with the aim of improving the interpretation and inversion methods in MCSEM.

Introduction

Geophysical inversion is an essential tool for estimating subsurface geological structures based on collected or simulated data. Despite advances in inversion methods (Constable et al., 1987; Marquardt, 1970; Silva et al., 2014), its high computational cost requires a prior assessment of data quality. A common approach is the use of singular value decomposition (SVD) in the sensitivity matrix, allowing the analysis of null spaces, which indicate the potential success of the inversion.

This study focuses on hydrocarbon prospecting in marine environments. To this end, the MCSEM method stands out. In this method, a horizontal electric dipole (DEH) is towed by a ship close to the seabed, while receivers distributed on the ocean floor record the electromagnetic response generated (Constable and Srnka, 2007). This includes the electric ($\vec{E}$) and magnetic ($\vec{B}$) fields, coupled by Maxwell's equations. Although the majority of studies focus on analyzing the electric field for inversion (Gribenko and Zhdanov, 2007; Silva Crepaldi et al., 2011), the magnetic field, which is still little explored, can provide valuable additional information due to its sensitivity to different properties of the medium.

The aim of this work is to evaluate the quality of the information that the magnetic field can contribute to the inversion with MCSEM data. To this end, an SVD analysis was carried out on the Jacobian matrices generated with the electric and magnetic fields, separately and simultaneously. Simulations of the direct problem were carried out using the vector finite element method with tetrahedral elements. The models generated have TIV anisotropy.

Methodology

The Marine Controlled-Source Electromagnetic method (MCSEM) is used to prospect for hydrocarbons in marine environments. It operates at low frequencies, generally between 0.1 and 10 Hz. Data acquisition is carried out using lines of receivers distributed geometrically over the ocean floor, which record the electromagnetic response generated by a horizontal electric dipole (DEH).This dipole is towed close to the seabed by a ship, emitting an electromagnetic field that interacts with the geological structures in the marine subsurface (Constable and Srnka, 2007)

The responses collected by the receivers (electric and magnetic fields) are used to estimate the physical properties of the environment through geophysical inversion. In order to analyze the quality of the information provided by this data, we used the mathematical technique of Singular Value Decomposition (SVD), which is applied to the Jacobian matrix, also known as the sensitivity matrix. This can be calculated by differentiating the system of equations that formulate the solution in relation to the parameters as shown in (Gomes and Silva, 2021).

To arrive at the Jacobian matrix, it is necessary to model the method directly. In the numerical modeling, frequencies of 0.25, 0.50, 0.75 and 1.0 Hz were used. The MCSEM modeling was carried out using the vector finite element method, with tetrahedral element meshes generated by the TetGen software. Both simulated models have TIV anisotropy, i.e. the physical properties vary with the vertical and horizontal directions, in the simulated cases the physical property that varies is the resistivity ρ .

SVD is a widely used mathematical tool for analyzing null spaces generated from synthetic data or real data acquired in the field. This technique makes it possible to evaluate the structure of the sensitivity matrix associated with the inversion problem, which provides crucial information on the stability of the solution and the model's resolution capacity, helping to identify which parameters are well determined by the data.

If $A \in \mathbb{R}_{m\times n}$ is a rectangular matrix, we can decompose the matrix A as follows:

$$A = UDV^T \tag{1}$$

where the matrices U and V are square matrices of dimension m and n respectively, where U consists of the eigenvectors to the right of A and V consists of the eigenvectors to the left of A, D is a matrix with the same dimension as A, where the main diagonal consists of the singular values σ of A sorted in descending order ($\sigma_1 > \sigma_2 > ... > \sigma_n$).

Results

Two different geological scenarios were simulated. The first model consists of a 1 km water depth, a 2.25 km thick sediment layer, followed by a 1 km thick salt layer and, below this, a semi-infinite sediment layer, as illustrated in Figure 1a. The arrangement has five transmitter lines (Tx) with 5 transmitters on each line, distributed at positions -4 km, -2 km, 0 km, 2 km and 4 km in the x direction and -3 km, -1 km, 1 km and 3 km in the y direction. The receiver lines (Rx) are at positions -4 km, -2 km, 0 km, 2 km and 4 km in the y direction, extending from -15 km to 15 km in the x direction, each receiver line has 150 Rx (Figure 1b).

The graphs (figure 2) for model 1 illustrated in figure 1a represent the null spaces produced by the $\vec{E}$ and $\vec{B}$ fields together (black curve), by the $\vec{B}$ field alone (blue curve) and by the $\vec{E}$ field alone (red curve). You can see that the graph in figure 2a has a smaller amplitude than the graph in figure 2b, which suggests that the vertical direction carries more information than the horizontal direction. It can be seen that in the vertical direction the null spaces of the magnetic and electric fields are almost identical, but the magnetic field has a subtly greater amplitude than the electric field.

The second model shows a water depth of 1.2 km over a layer of sediment with bathymetry. It includes two resistive bodies: the first at a depth of 1.9 km and a thickness of 100 m, and the second at a depth of 2.5 km and a thickness of 200 m (Figure 3a). The arrangement has four transmitter lines (Tx) at positions 0 km, 3 km, 6 km and 9 km in the x and y directions. The receiver lines each

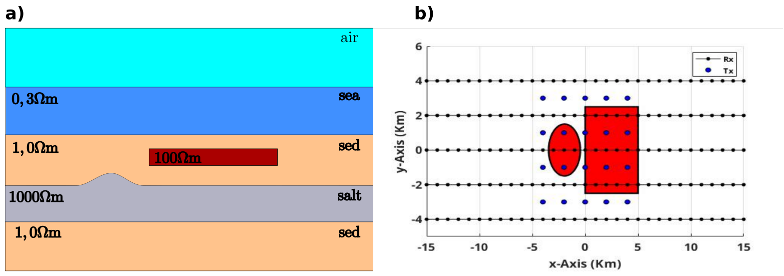

Figure 1: Model 1

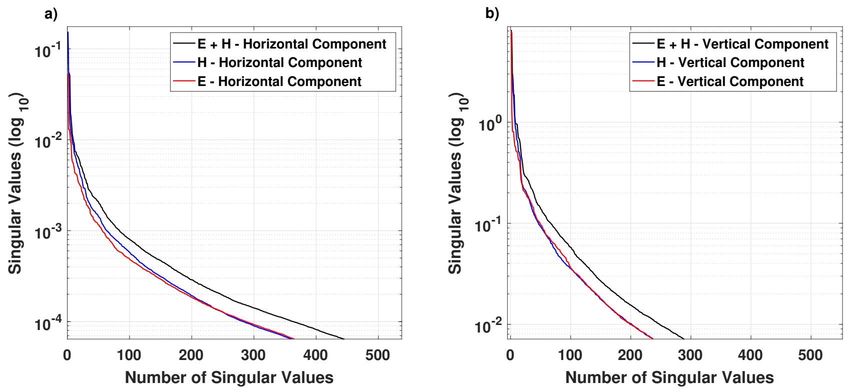

Figure 2: Graph a) refers to the SVD of model 2 of the horizontal components of the electric field, magnetic field and both fields, while graph b) refers to the SVD of the vertical components of the same fields.

have 150 receivers (Rx) at positions -1.5 km, 1.5 km, 4.5 km, 7.5 km and 10.5 km in the y direction, extending from -5 km to 20 km in the x direction (Figure 3b).

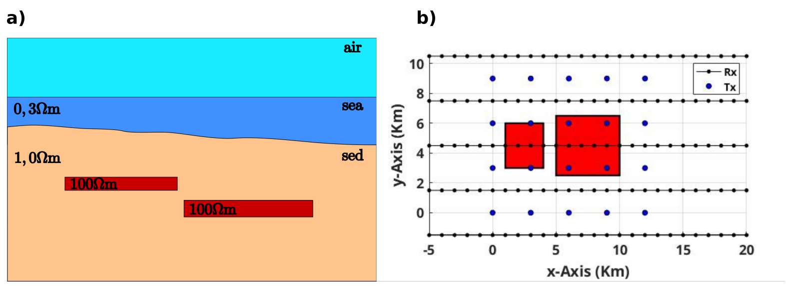

Figure 3: Model 2

The graphs (figure 4) for model 2 illustrated in figure 3a, represent the null spaces produced by the $\vec{E}$ and $\vec{B}$ fields together (black curve), by the $\vec{B}$ field alone (blue curve) and by the $\vec{E}$ field alone (red curve). As with the graphs in figure 2, the null spaces in graph 4a, have smaller amplitudes compared to graph 4b. This indicates that the vertical components of the fields carry more information than the horizontal components. In the graph of the vertical components, it can be seen that the null spaces of the $\vec{B}$ field have a greater amplitude than the null spaces generated by the $\vec{E}$ field, suggesting that

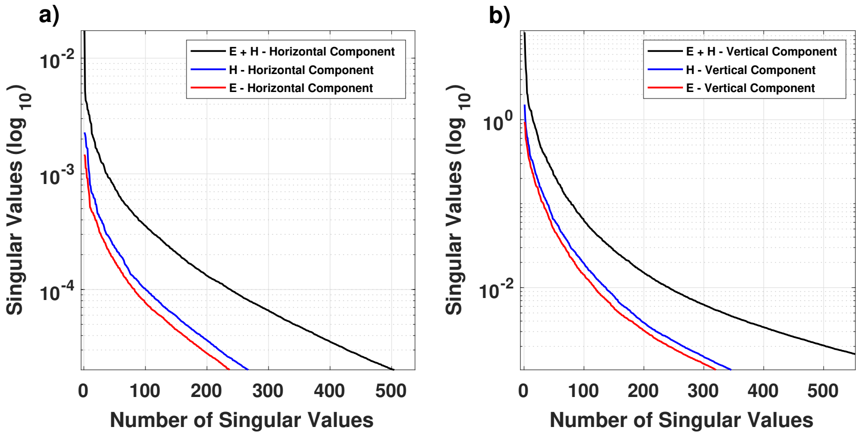

Figure 4: Graph a) refers to the SVD of model 2 of the horizontal components of the electric field, magnetic field and both fields, while graph b) refers to the SVD of the vertical components of the same fields.

the magnetic field has more information.

Conclusions

The analysis of the null spaces obtained through the decomposition into singular values in the two models indicates that the vertical component of the $\vec{B}$ magnetic field is a promising candidate for future inversions of geophysical data, offering more detailed information on the physical properties of the medium than that provided by the $\vec{E}$ electric field.

A future step towards the conclusion of this work is the inversion of data based on the information obtained from the analyses carried out on the null spaces, in both models, from the SVD applied to the Jacobian matrix, as well as a more robust and realistic simulation of geological models in the marine subsurface.

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