2.5D Modeling of data for the Electromagnetic Multi-Frequency Method - EMMF

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Abstract

We present the numerical modeling of the fields from a very large circular loop of current, over a two-dimensional earth. This source is used in the Electromagnetic Multi-Frequency Method, a new method aimed at the geophysical prospecting for oil and other mineral deposits reaching depths of a few kilometers. The loops used in this method have radii of hundreds of meters. We have employed finite elements in a 2.5D formulation to calculate the radial magnetic field generated by such a source on the surface of the terrain. The EMMF method measures the field at distances of up to 10km from the source. Our results illustrate the capability of those measurements to detect the inhomogeneities in the stratified earth.

Introduction

The Electromagnetic Multi-frequency Method (EMMF) is an innovative, new method for imaging the distribution of the electromagnetic properties of the subsurface. The method is currently being developed as a joint effort of the Universidade Federal da Bahia, Universidade Federal do Pará and Universidade Estadual Norte Fluminense Darcy Ribeiro, in a project financed by PETROBRAS.

The EMMF is a frequency domain method that employs a large loop of current placed on the surface to generate the electromagnetic fields that will diffuse through the earth. The method measures the radial component of the magnetic field on the surface and uses this information to build two different sections of data: (1) for every source-receiver separation and every frequency, we determine an apparent resistivity value and the coordinates of the point to which that value is associated (Machado, 2009) in the earth. By spanning a large distance from the source (up to a projected 10km in the new system) and a wide range of frequencies (from 0.1Hz to 1000Hz), we are able to build an apparent resistivity section representative of the distribution of the real resistivities of the earth; (2) also for every horizontal position and frequency we measure the spectral induced polarization effect and calculate a polarization parameter that is plotted on an IP section representative of the distribution of the polarization characteristics of the earth.

The method is intended to detect and delineate structures formed by variations in the resistivity and polarizability of the sub-surface. It has been successfully applied in the mature oil fields of the Recôncavo sedimentary basin, in the state of Bahia, Brazil (Dias et al., 2005, 2006). Its apparent resistivity and polarization sections can be interpreted and checked against the known facts about the geology and the geophysics of the area.

Now, we are modeling the data of the EMMF method over 2D environments. We have applied the finite element method, in a 2.5D formulation of the fields from the loop. In this paper we show our first results from this work.

2.5D finite element formulation

In a general 3D or 2D environment, the horizontal loop of current generates an essentially three-dimensional field geometry, where all components vary in every direction. However, when we calculate those fields in a medium formed by homogeneous parallel horizontal layers, the problem is reduced to a 1D problem, because, then, it has a perfect cylindrical symmetry and every component is invariant relative to the azimuthal angle (θ).

In order to formulate the problem of calculating the fields of the horizontal loop in a bi-dimensional model, we take advantage of the solution for the 1D layered medium, by building the model as a layered background in which are placed infinitely long homogeneous bodies. We separate the field in two parts, that we call primary and secondary fields: the fields that would be present if the model were formed only by the background layers is the primary one; the secondary field is the difference between the total actual field and the primary. When we make this separation, we are able to write our second order differential equations on the secondary fields, having the primary ones as the source term.

We have applied the finite element scheme described in Rijo (2005), Mitsuhata (2000) and Shen and Sun (2008): we employ the Fourier Transform to our equations, changing the problem from the spatial coordinate on the strike direction (in our case, coordinate y) into the corresponding spectral coordinate (λ_y). By performing this transformation, we are able to reduce the problem to only two coordinates (x, z) and then solve this 2D problem for each value of the coordinate λ_y that is needed to calculate the inverse transform.

We build a set of two coupled differential equations on the two components of the secondary field in the y direction ($E_y^s(x,\lambda_y,z)$ and $H_y^s(x,\lambda_y,z)$). We solve for these using our finite elements and then calculate the remaining components from them. For the modeling of EMMF data, we only need the radial component of the magnetic field on the surface (H_x).

In short, the modeling work is divided in the following steps:
(1) calculate the fields in the 1D layered medium in normal spatial coordinates. We need these to be added to the secondary fields to compose the total fields;
(2) calculate the fields in the 1D layered medium in the domain of the Fourier Transform. These are used as primary fields in our finite element scheme;
(3) discretize the entire medium, including the air, and calculate our finite element solution for the nodes in the whole grid, using Dirichlet homogeneous boundary conditions;
(4) calculate $H_x^s(x,\lambda_y,z)$ by taking the numerical derivatives of the calculated components in Maxwell's equations;
(5) calculate the inverse Fourier transform to obtain the secondary field components in the spatial domain and add those to the primary field components from step (1).

Results

With the modeling shown here, we have generated data that can be processed in order to generate apparent resistivity sections. We present the amplitudes of the radial magnetic field components in 2 models, to explore the detectability of the bodies by that component.

In all models shown here, the source is a circular loop with a radius of $340m$, that stays fixed in one position. We show the amplitude of the horizontal magnetic field component (H_x) normalized by the direct coupling between source and receiver, i.e. the field that would be measured in the same separation in a vacuum, to which we refer as H_z^0.

Model 1

This model is formed by one conductive body in a two-layer earth (figure 1). Frequency ranges from 0.1Hz to 1000Hz. The conductive body is very well detected, as shown in figure 2. In both extremes of the frequency range, the body has almost no influence on the data, but its presence is strongly felt in the frequencies from 10Hz to 100Hz, approximately.

The processing of this data by the EMMF method will generate an apparent resistivity section, migrating from frequency to depth, and locating the anomalous body. This work will allow us a measurement of the deviation of the processed image from the real location of the body, which, in turn, will be useful in the refinement of the method.

Model 2

Our second model has three anomalous conductive bodies in a layered environment, as shown in figure 3.

We have selected eight frequencies to analyze the field responses, from 0.1Hz to 30Hz. The results are shown as the curves in figure 4. The general behavior of the amplitude in each case, disregarding the bodies in the model, shows an increase in the strength of the signal, followed by the expected decrease, which is clearly seen in the higher frequencies, from 5Hz up. For this behavior to be perceived in the lower end of the frequencies, greater distances would have to be reached in the figure.

Naturally, the lower frequencies will show the smoothest curves. We can clearly observe the influence of the first and third conductive bodies, which are closer to the surface, in every curve, with that influence increasing with frequency. The second body, with the same resistivity as the other two, but located in a greater depth, shows its stronger influence in the intermediate range, from 2Hz to 10Hz.

The section of the normalized amplitude for this model is shown in figure 5. We observe that the horizontal positioning of each anomalous body is correctly determined in the section. Again, the complete spatial location of the bodies will be estimated by the processing of the EMMF method.

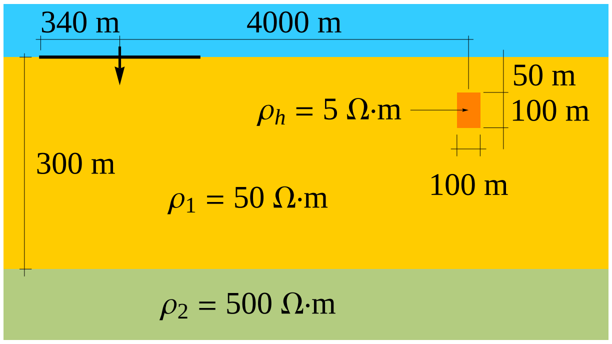

Figure 1: Model 1

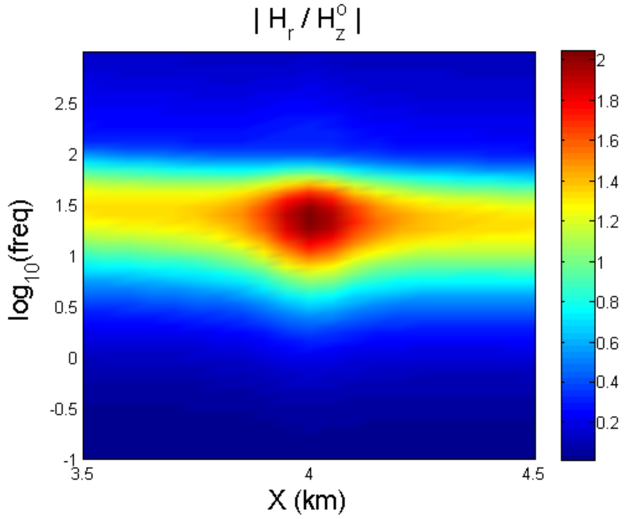

Figure 2: Normalized amplitude section for model 1

Conclusions

The curves and sections shown here are the first results of our modeling of data for the EMMF method. These data, and those from other models, are being processed as of this writing, and the resulting sections will be the shown when this work is presented.

The next step in this research is the inclusion of the polarization effects in our models, so that we can generate both apparent resistivity and induced polarization sections for each model. After that, our goals are to use the data in an inversion process to fine tune the location of the anomalies observed in the sections and to repeat the previous steps with three-dimensional models.

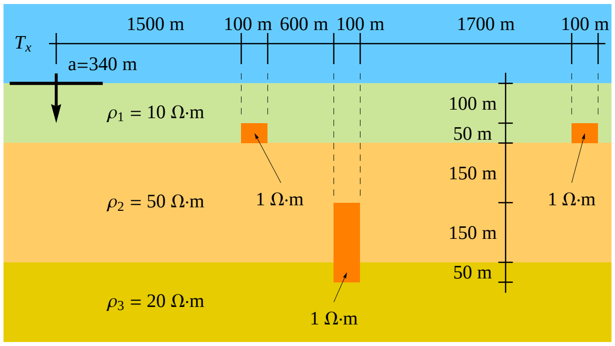

Figure 3: Model 2

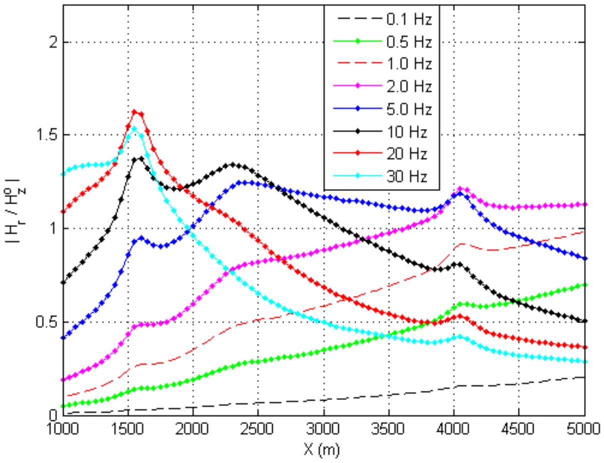

Figure 4: Normalized amplitudes for model 2 in eight frequencies.

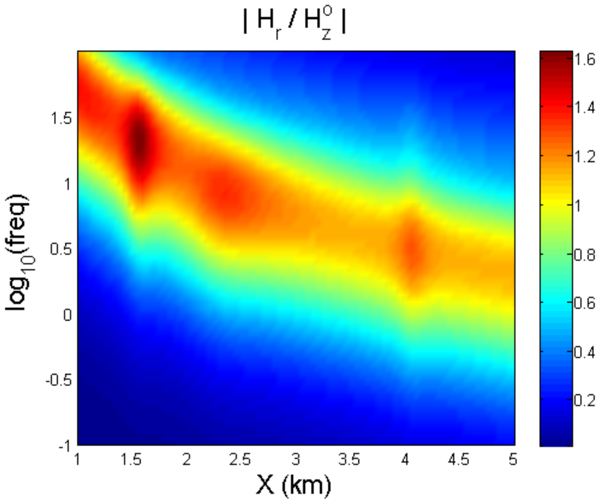

Figure 5: Normalized amplitude section for model 2

Acknowledgments

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