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Sensitivity of Magnetic Dipole Fields to Magnetic Permeability

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Abstract Summary

This work presents an analysis of the sensitivity of the magnetic field from frequency domain magnetic dipoles in relation to magnetic permeability in a configuration based on the EM-34 equipment. The performed tests focused on evaluating the depth to which a given layer in a stratified medium exhibits a significant sensitivity response. This analysis is fundamental for determining the resolvability of the target layer in inversion processes and its influence on the data collected in different configurations and frequencies.

Introduction

Magnetic permeability is a fundamental physical property in the geophysical characterization of the subsurface, especially in environments with ferromagnetic materials. When neglected in electromagnetic inversion processes, it can lead to incorrect interpretations (Beard and Nyquist, 1998; Farquharson et al., 2003).

The sensitivity of the electromagnetic field in relation to magnetic permeability provides information about the resolution capacity of magnetic layers at different depths. In this context, a sensitivity analysis is essential, prior to any inversion work,

This work investigates how the relative permeability of a layer affects the response of the magnetic field generated by magnetic dipole sources at different frequencies and arrangement configurations. Using a three-layer model and the operational configurations of the EM-34 equipment, we evaluate the depth to which the target layer produces a significant sensitivity response, considering both vertical (DMV) and horizontal (DMH) magnetic dipoles.

Method

Sensitivity is defined here as the derivative of the magnetic field with respect to the medium permeability. It is obtained from the derivative of the analytical formulation presented by Ward and Hohmann (1988) for stratified 1D models, considering magnetic dipoles as the source, in coplanar configurations. Using a horizontal magnetic dipole (HMD), with dipole moment oriented along the y axis, the H_y component of the field is calculated; whereas using vertical magnetic dipole (VMD), the H_z component is determined. Both expressions are derived in relation to the relative magnetic permeability. The fields are normalized by the primary field in vacuum, so that the sensitivity expression takes the form:

$$\frac{\partial}{\partial \mu_r}\left(\frac{H_z^{(0)}}{H^p}\right) = -r^3 \int_0^\infty \frac{1}{u_0}\frac{\partial R_{TE}^{(0)}}{\partial \mu_j} e^{u_0(z+h_0)} k_r^3 J_0(k_r r) dk_r, \quad (1)$$

$$\frac{\partial}{\partial \mu_r}\left(\frac{H_y^{(0)}}{H^p}\right) = (r^2 - 2y^2) \int_0^\infty -u_0 \frac{\partial R_{TE}^{(0)}}{\partial \mu_j} e^{u_0(z)} J_1 dk_r, \quad (2)$$

$$H^p = -\frac{m}{4\pi r^3}. \quad (3)$$

The terms J_0 and J_1 are Bessel functions; z represents the depth of the receiver; h_0 is the height of the source relative to the surface interface; $r = \sqrt{(x^2 + y^2)}$ is the distance between the receiver and the source; k_r is the variable of the Hankel transform; $u_0 = \sqrt{k_r^2 - k_0^2}$, where $k_0 = \sqrt{i\omega\mu_0\sigma_0}$ is the wave number of the air layer; and H^p is the coplanar primary field in a vacuum.

The integrals are calculated using filtering techniques, specifically employing the 201-point filter presented by Werthmüller et al. (2019). The configurations used are that of the EM-34 equipment, which defines a frequency for each offset, so that for a homogeneous half-space, all three configurations measure at the same induction number (Table 1).

Table 1: EM-34 settings.

Spacing between coils (m)	Depth of exploration (m)		Frequency (Hz)
	Horizontal dipole	Vertical dipole	
10	7,5	15	6400
20	15	30	1600
40	30	60	400

Results

In order to evaluate the influence of magnetic permeability on the magnetic field measured by magnetic dipole arrays, a model composed of three horizontal layers was considered (Fig. 1). The layers are arranged vertically, with the first and third layers having a relative magnetic permeability ($\mu_r = \mu/\mu_0$) equal to $\mu_r = 1$, equivalent to that of a vacuum, i.e., $\mu = 4\pi \times 10^{-7}$ H/m. The second layer has variable permeability, which is the focus of the sensitivity analyses in this work. The two relative permeability values of the second layer are $\mu_r = 1$ (reference value, equivalent to vacuum) and $\mu_r = 1.3$, symbolizing a highly ferromagnetic layer (Guillemoteau et al., 2016). The thickness of the second layer was set at $h_2 = 5$ m, and the depth of its top interface plane was varied from 10cm to 60 meters.

The heights of the coils relative to the surface are $h_0 = 0{,}5$ m, and the spacing between them is indicated by s, with the values referring to the EM-34 configuration (Table 1). The third layer is a homogeneous half-space. The electrical resistivity ρ is kept constant in all layers, equal to $100\ \Omega$m, in order to isolate the effects of magnetic permeability on the field responses.

To analyze the influence of magnetic permeability on the measured field, two tests were performed considering a stratified medium (Fig. 1), where we calculated the field sensitivity while varying the values of μ_r and depth of the target layer.

The plots in Figure 2 show the sensitivity of the magnetic field in relation to the relative magnetic permeability referring to the second layer as a function of depth, considering both the DMV (Fig. 2a) and DMH (Fig. 2b).

The graphs in Figure 2 show that the sensitivity of the magnetic field to relative permeability decreases with increasing depth and μ_r. In all cases, the maximum sensitivity is highest when $\mu_r = 1$ (solid lines) and lowest when $\mu_r = 1.3$ (dashed lines), and the depth of maximum sensitivity is the same for both values of μ_r. In addition, the horizontal magnetic dipole has higher sensitivity values than the vertical dipole. The curves also indicate that, as the depth grows from the surface down, the greatest sensitivity occurs at increasing offsets and decreasing frequencies.

In the case of the DMV, negative sensitivity values were observed, indicating that the effect of relative magnetic permeability (μ_r) acts to decrease the field. These negative values occur in the shallower regions and, at these depths, the sensitivities associated with $\mu_r = 1.3$ are greater than

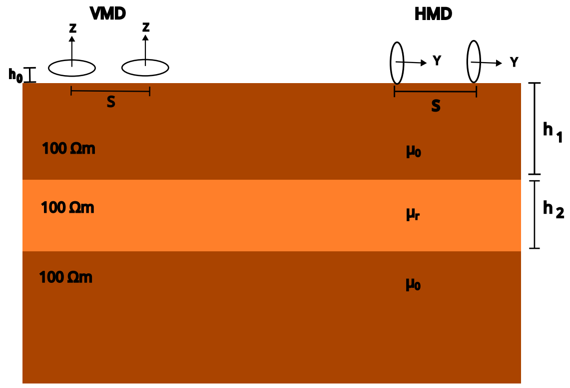
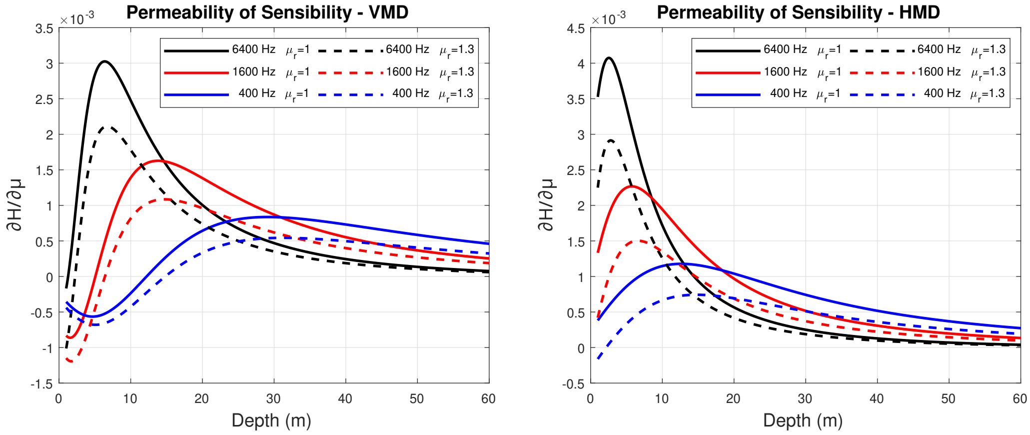


Figure 1: Representation of the three-layer model used in sensitivity testing.



(a) Vertical magnetic dipole

(b) Horizontal magnetic dipole

Figure 2: Magnetic field sensitivity as a function of depth for DMV (a) and DMH (b). Colors indicate frequency: 6400 Hz (blue), 1600 Hz (green), 400 Hz (red). Solid lines correspond to $\mu_r = 1$; dashed lines correspond to $\mu_r = 1.3$.

those for $\mu_r = 1.0$. On the other hand, when the effect of relative magnetic permeability acts to strengthen the field (i.e. positive sensitivity), the greatest influence occurs for $\mu_r = 1.0$.

In the DMV results (Figure 2a), the sensitivity is highest for the 6400 Hz, 10 m configuration for depths rangin from zero to approximately 13 m. For depths between 13 and 30 m, sensitivity is highest at the 1600 Hz, 20 m configuration, and below 30 m, the highest sensitivity values occur at 400 Hz, 40 m.

In the case of the DMH (Figure 2b), a similar pattern is observed, but with different depth ranges: the 6400 Hz, 10 m configutation has greater sensitivity up to about 8 m; between 8 and 17 m, sensitivity is greatest at 1600 Hz, 20 m; and at greater depths, the 400 Hz, 40 m configuration becomes more sensitive.

These behaviors are related to the facts that the magnetic field lines which are felt at the receiver reach greater depths with increasing offsets, and that field attenuation is stronger in higher frequencies.

Conclusions

In this work, an analysis of the sensitivity of the magnetic field with respect to magnetic permeability in a stratified medium was performed, considering a specific target layer. The calculation of the magnetic field was based on the configurations of the EM-34 equipment, using magnetic dipoles in the horizontal (DMH) and vertical (DMV) orientations as sources. For this investigation, the magnetic permeability of the layer and its depth were varied.

The results show the depth ranges for which each frequency/depth configuration has the maximum sensitivity to the target layer. Higher frequencies, such as 6400 Hz, are more sensitive to shallow layers, while lower frequencies, such as 400 Hz, allow for the investigation of deeper layers. In addition, it was observed that DMH arrangements generally have greater sensitivity compared to DMV arrangements.

This analysis is important for estimating the resolvability of magnetic layers in electromagnetic inversion processes and can assist in choosing more effective data acquisition configurations.

Acknowledgments

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