Modeling the geomagnetic fields under the Equatorial Electrojet perpendicular to the strike of a 2-D structure

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Abstract

One of important electromagnetic method used in subsurface geophysical investigation in regional scale is the Magnetotelluric Method (MT). In this method, the primary electromagnetic induced field is supposed to be laterally uniform and it is considered as plane waves. However, in equatorial latitudes, the geomagnetic fields shows an strong enhancement associated with ionospheric electrical currents, termed Equatorial Electrojet (EEJ), which can made the primary fields nonuniform.

In this work, we analyze the influence of a 2-D structure perpendicular to an electrojet, which was modeled as infinite current line and as planar gaussian distribution of current. The finite element method was used for numerical modeling. The response of the two electrojets upon the geomagnetic field scattered by 2-D structure are show in profile for B and E fields.

With that problem's solution in addition with our previous work we can determinate, by a vectorial sum of the fields, the geomagnetic response of a 2-D heterogeneity that has any strike orientation. Afterwards, we can, with two fields polarization, obtain the impedance tensor and show the profiles for phase and resistivity.

Introduction

One of most important electromagnetic method used in subsurface geophysical investigation in regional scale is the Magnetotelluric Method (MT), proposed by Tikhonov (1950) and Cagniard (1953). In this method the primary electromagnetic induced field is supposed to be laterally uniform and it is usually considered as plane waves. However, in equatorial latitudes, the geomagnetic fields shows an strong enhancement associated with ionospheric electrical currents, termed Equatorial Electrojet (EEJ), which can made the primary fields nonuniform.

Because the plane-wave assumption may not be applicable in the equatorial regions, several authors have studied the source effects on MT response in continental regions. Hermance & Peltier (1970) employed an infinite line current in E-W direction, localized at 110 km above earth's surface, to represent an concentrated EEJ. Peltier & Hermance (1971) supposed the EEJ like an superficial current density according to one planar gaussian distribution, at 110 km of altitude and flowing in the E-W direction. They concluded that the source effect decreases with the distance from Electrojet center and increase both, when the media resistivity of subsurface and period of waves became greater. Hibbs & Jones (1973a) found the electromagnetic response of 2-D heterogeneity and demonstrated for period higher than 10 s that source configuration influences the field values at subsurface. Mota & Rijo (1991) concluded that deepest 2-D structure response is affected by the medium host response but the shallow lateral heterogeneity response due to plane wave is not affected. Padilha *et al.* (1997) demonstrated that the EEJ theoretical distortions are overestimated and the use of the classical MT theory can be employed in period band (0.001 to 2000 s) used for lithospheric studies. Silva & Rijo (2001) evaluated numerically the influence of the electrojet upon the geomagnetic response of 2-D structures and computed the ratio between the vertical and horizontal components of magnetic field.

In all these previous studies, the EEJ was modeled parallel to strike. In that case, the induced field presents only the TE mode. However, that is a very restrictive geological situation because a 2-D structure can has any strike orientation.

So our aim in this work is to evaluate numerically by finite element method the geomagnetic response of 2-D structure perpendicular to electrojet in E-W direction. We show the fields E and B calculated at earth's surface, modeling the electrojet as infinite line current and as a gaussian distribution of current density located at 110 km above the earth's surface.

Methodology

The electromagnetic theory shows that the fields associated to infinite source current perpendicular to a 2-D heterogeneity presents coupled both TE and TM modes. In such case, the problem is essentially 3-D but can be turned into several straightforward bi-dimensional problems by Fourier Transform. The final solution is obtained computing an inverse Fourier transform from all these 2-D responses by the linear digital filter technique.

A current line located at 110 km of altitude in the E-W direction can be considered as a good model of a concentrated electrojet (Hermance & Peltier, 1970). However, Hibbs & Jonnes (1973a) and Peltier & Hermance (1971) regard a planar gaussian current distribution with standard deviation of 240 km, located at 110 km above earth's surface, as a more adjusted model to the electrojet. In such a case, we obtain the total response by integration of all individual responses of each current line, with the intensity changing in accord to gaussian distribution (Mota & Rijo, 1991).

In this work we use the finite element method to determine the geomagnetic fields under the equatorial electrojet perpendicular to a 2-D heterogeneity. The primary and secondary fields have been separated to increase the numerical solution's stability (Rijo, 1989).

The primary electrical field is given by the stratified media response (Ward & Hohmann, 1988). The integrals associated with the primary field components were calculated by the linear digital filter technique (Nissen & Enmark, 1986; Rijo, 1989).

From Maxwell's equations in the k_y spatial Fourier domain, the secondary fields are governed by the equations:

$$-\frac{\partial}{\partial x}\left(\frac{\hat{z}}{u^2}\frac{\partial \hat{H}_y^s}{\partial x}\right)-\frac{\partial}{\partial z}\left(\frac{\hat{z}}{u^2}\frac{\partial \hat{H}_y^s}{\partial z}\right)+\hat{z}\hat{H}_y^s+$$

$$\frac{\partial}{\partial x}\left(\frac{ik_y}{u^2}\frac{\partial \hat{E}_y^s}{\partial z}\right)-\frac{\partial}{\partial z}\left(\frac{ik_y}{u^2}\frac{\partial \hat{E}_y^s}{\partial x}\right)=\frac{\partial}{\partial z}\left[\frac{\hat{z}}{u^2}(\sigma-\sigma_p)\hat{E}_x^p\right]$$

and

$$-\frac{\partial}{\partial x}\left(\frac{\sigma}{u^2}\frac{\partial \hat{E}_y^s}{\partial x}\right)-\frac{\partial}{\partial z}\left(\frac{\sigma}{u^2}\frac{\partial \hat{E}_y^s}{\partial z}\right)+\sigma\hat{E}_y^s-$$

$$\frac{\partial}{\partial x}\left(\frac{ik_y}{u^2}\frac{\partial \hat{H}_y^s}{\partial z}\right)+\frac{\partial}{\partial z}\left(\frac{ik_y}{u^2}\frac{\partial \hat{H}_y^s}{\partial x}\right)=\frac{\partial}{\partial x}\left[\frac{ik_y}{u^2}(\sigma-\sigma_p)\hat{E}_x^p\right]$$

where σ_p and σ are, respectively, the homogeneous and heterogeneous medium conductivities; $\hat{z}$ is the medium impeditivity; $u^2=k_y^2+i\omega\mu\sigma$ is a squared propagation constant, with k_y, ω and μ, respectively, wave number, angular frequency and magnetic permeability. In the right side of equations above, the term $(\sigma-\sigma_p)E_x^p$ represents the source of secondary field, where $\hat{E}_x^p$ is the primary field calculated within the heterogeneity. The others secondary fields are obtained by numerical differentiation using the identities:

$$\hat{B}_x^s=\mu_0\left(-\frac{ik_y}{u^2}\frac{\partial \hat{H}_y^s}{\partial x}+\frac{\sigma}{u^2}\frac{\partial \hat{E}_y^s}{\partial z}\right),$$

$$\hat{B}_z^s=\mu_0\left(-\frac{ik_y}{u^2}\frac{\partial \hat{H}_y^s}{\partial z}-\frac{\sigma}{u^2}\frac{\partial \hat{E}_y^s}{\partial x}\right),$$

$$\hat{E}_x^s=-\frac{ik_y}{u^2}\frac{\partial \hat{E}_y^s}{\partial x}-\frac{\hat{z}}{u^2}\frac{\partial \hat{H}_y^s}{\partial z},$$

$$\hat{E}_z^s=-\frac{ik_y}{u^2}\frac{\partial \hat{E}_y^s}{\partial z}+\frac{\hat{z}}{u^2}\frac{\partial \hat{H}_y^s}{\partial x}.$$

Finally, the total fields are obtained computing the inverse Fourier transform of secondary components and summing up them with the primary ones.

Model

In our experiments, we used the model shown in Figure 1 suggested by Prof. Arora (personal communication) to investigate the effects of the electrojet on the field's response. The model is composed of two bi-dimensional structures embedded in a 10 Ωm host covered by a 50 Ωm layer, with 2 km of thickness.

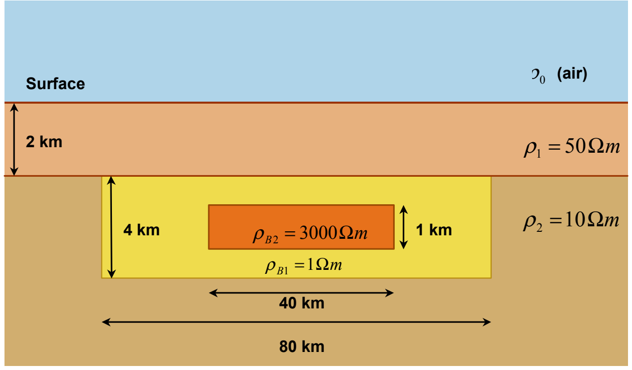

Figure 1 – Model of inhomogeneous semi-space (out of scale).

The external structure has 80 km of width, 4 km of thickness, 1 Ω-m of resistivity and is located at 2km from the surface. The internal structure has 40 km of width, 1 km of thickness, 3000 Ω-m of resistivity and is located at 3,5 km from the surface.

Results

We realized ours experiments with two kinds of sources: infinite current line and planar gaussian distribution of current. The line and the center of the gaussian distribution are located at y = 0 km. The position for field's profiles is located at y_0 = 500 km from the source, according to Figure 2. The heterogeneity's center is located at 500 km from a reference point in coordinate x. We present the results in form of profiles for the field E and B, computed at the surface for the frequencies 10^{-3} and 10^{-4} Hz. For frequencies higher than 10^{-3} Hz, the effects of the line and gaussian sources on the response do not change significantly.

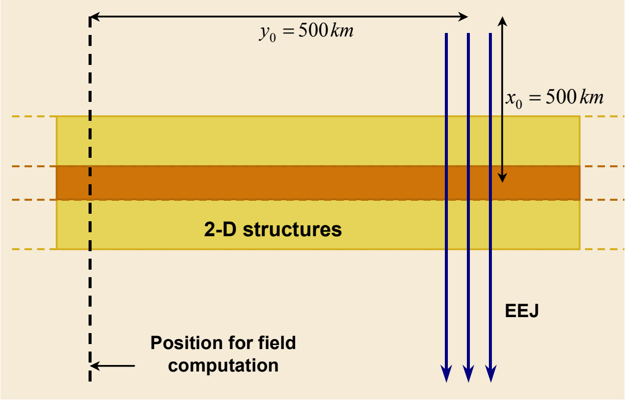

Figure 2: Distance for profiles computing.

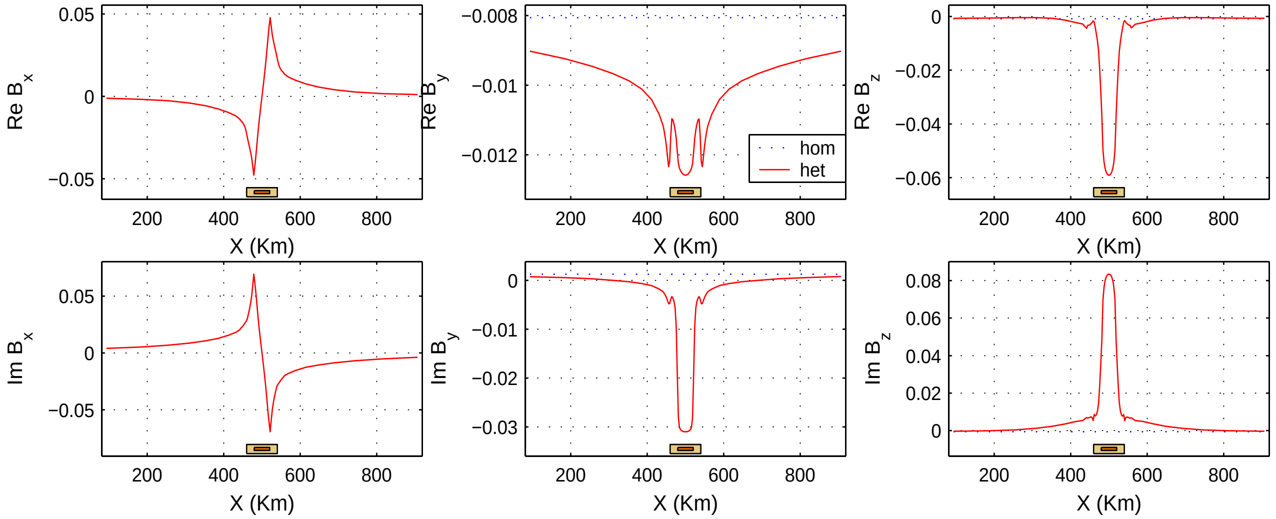

Figure 3 – Real and imaginary parts of the magnetic field for infinite current line. Frequency: 10^{-3} Hz.

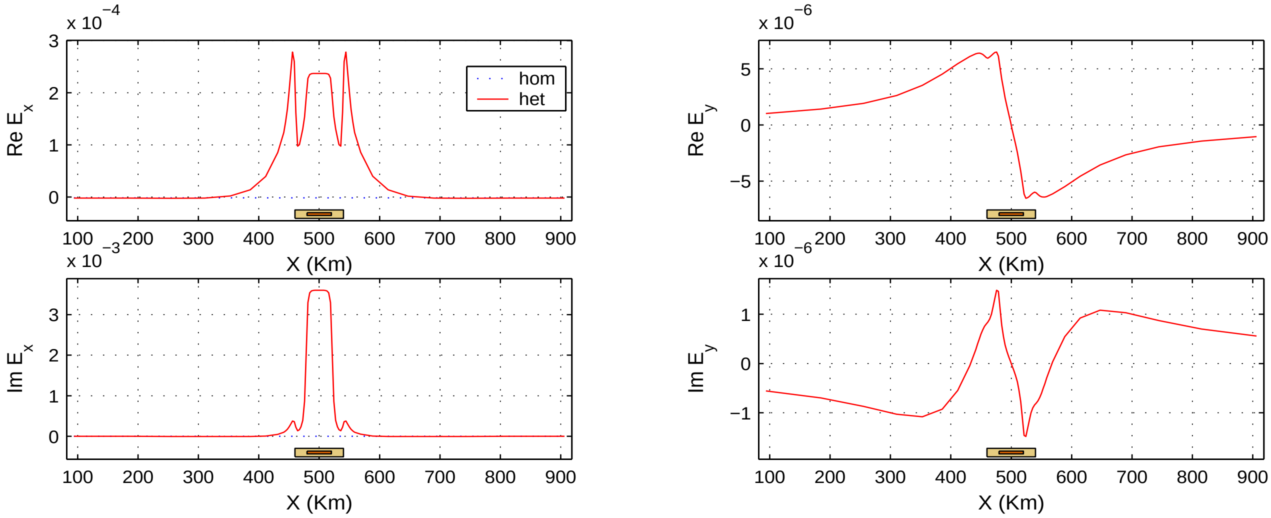

Figure 4 – Real and imaginary parts of the electric field for infinite current line. Frequency: 10^{-3} Hz.

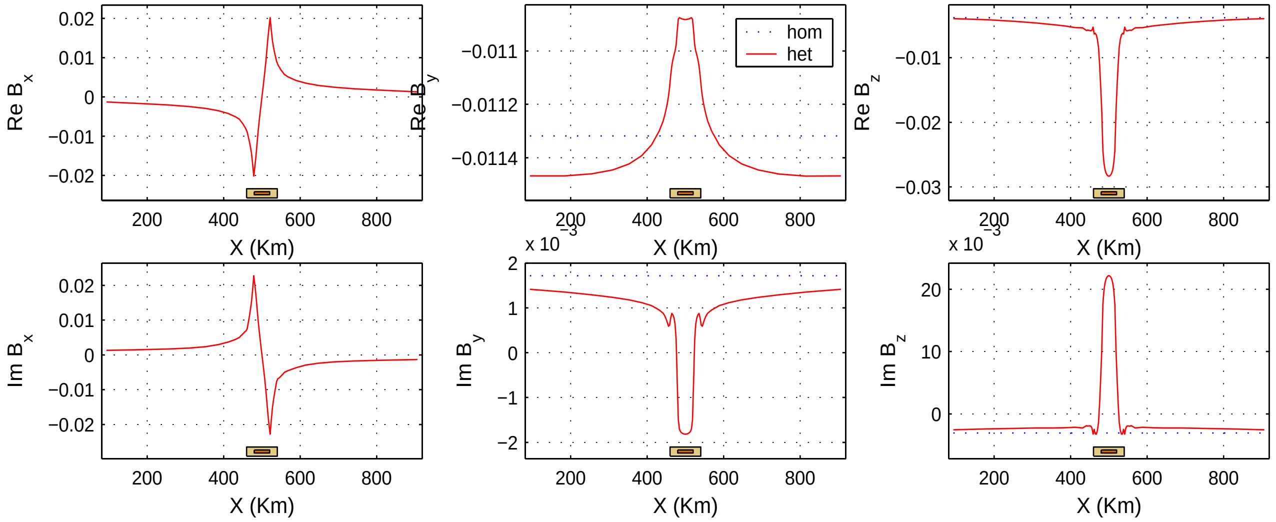

Figure 5 – Real and imaginary parts of the magnetic field for infinite current line. Frequency: 10^{-4} Hz.

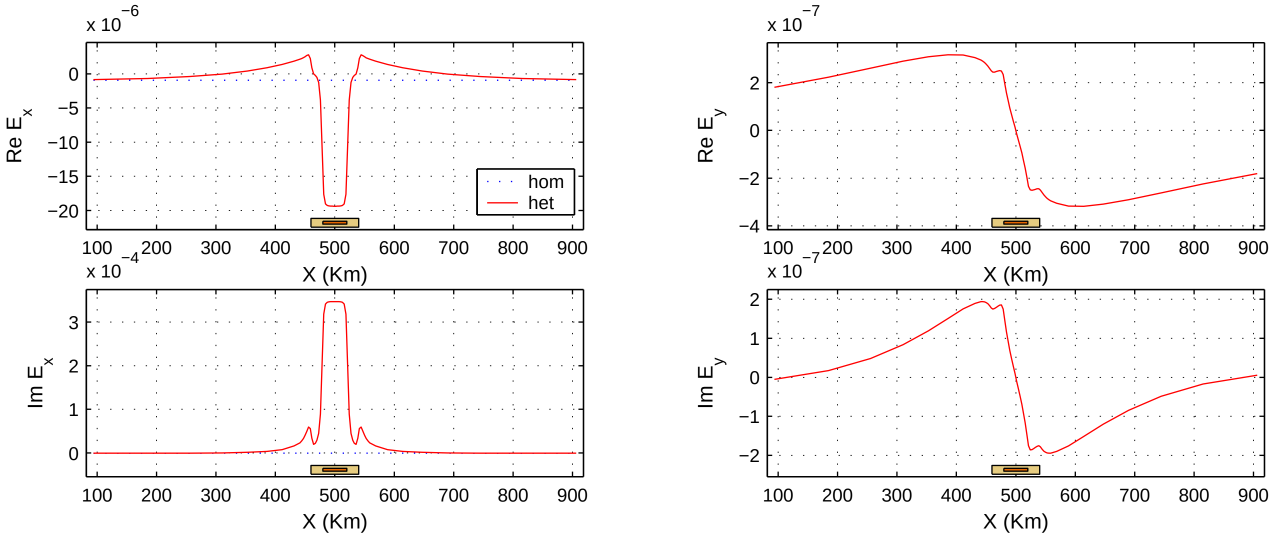

Figure 6 – Real and imaginary parts of the electric field for infinite current line. Frequency: 10^{-4} Hz.

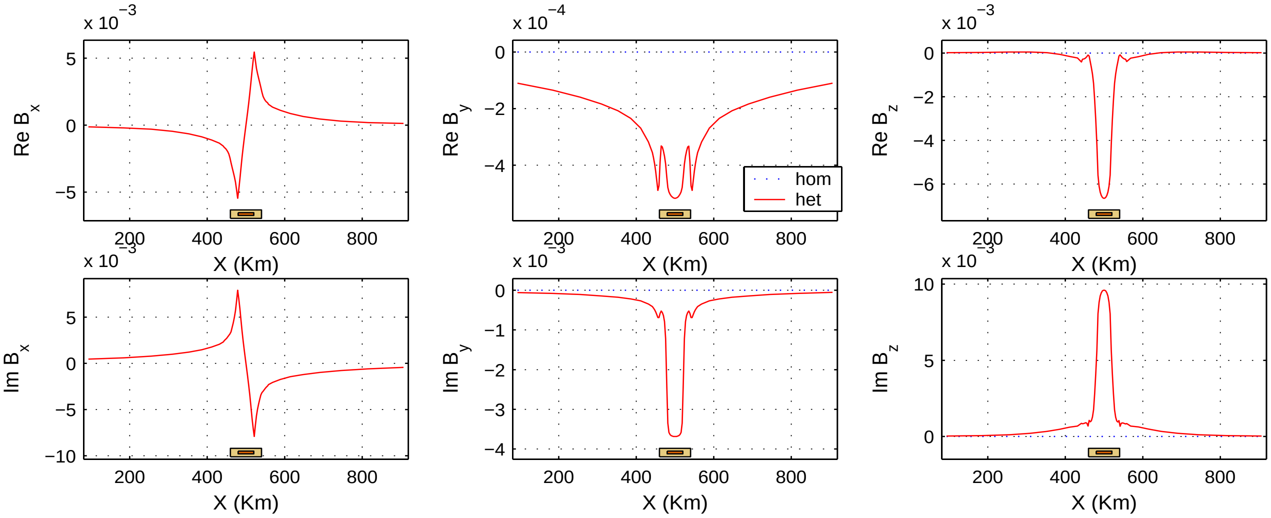

Figure 7 – Real and imaginary parts of the magnetic field for gaussian distribution. Frequency: 10^{-3} Hz.

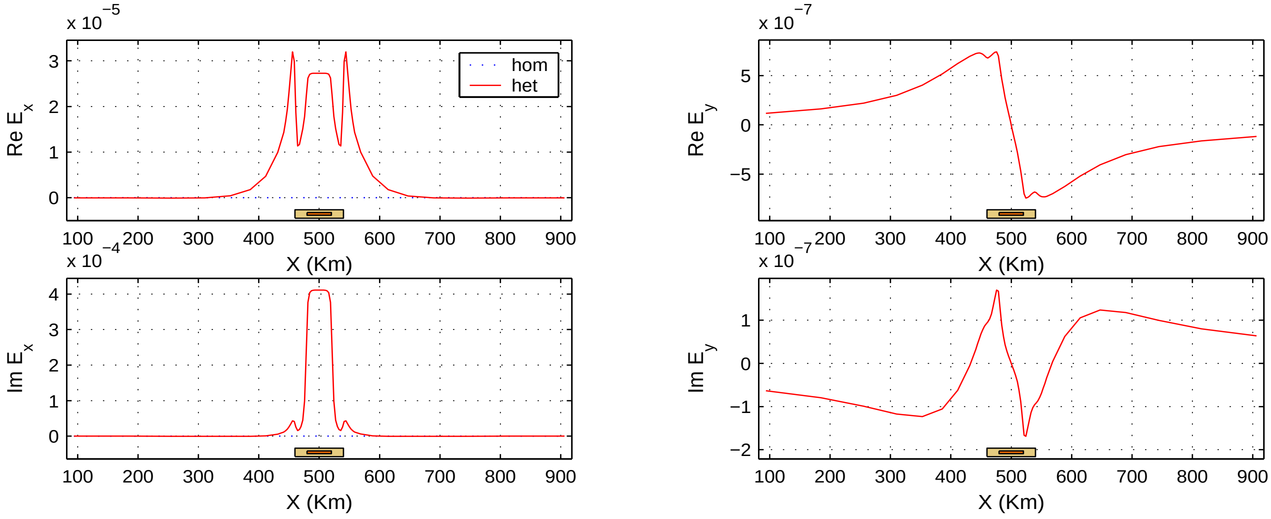

Figure 8 – Real and imaginary parts of the electric field for gaussian distribution. Frequency: 10^{-3} Hz.

In the Figure 3, using the infinite line current at 10^{-3} Hz, we observed that: the peaks of B_x component correspond to horizontal limit of the 40 km structure; the peaks in the real part of component B_y shows both external and internal structures limits; the high conductivity contrast for the internal structure cover up the external structure influence for B_z component.

In the Figure 4 we noted that the real part of E field shows peaks on the limits of the structures but, in imaginary part, the information about the external structure is no long clear. However, accentuated peaks are still present for internal structure. In conclusion, with infinite current line, some components can delineate the structures from its geomagnetic response.

Using the same model for the electrojet, but at 10^{-4} Hz, we observed for Figure 5 that the accentuated peaks still delineate the internal structure but, because the higher skin depth, the information about the large structure was lost. In the same way, in the Figure 6, the electric field components show a strong influence for the internal structures but we can't delineate the lateral limits.

In the Figures 7 an 8 we modeled the electrojet as planar gaussian distribution of current density at 10^{-3} Hz. Comparing with the infinite current line at the same frequency (figures 3 and 4) we noted that the responses change only in theirs intensity. The forms of profiles do not alter because the primary induced field doesn't vary in profile direction.

Conclusions

This work is a continuation of previous work by Silva & Rijo (2001) where was estimated the effects on the geomagnetic field response of an 2-D heterogeneity **parallel** to the electrojet. In this paper we solved the problem where the structure's strike is **perpendicular** to electrojet. This was accomplished with two models to simulate the electrojet: an infinite line of current located at 110 km above the ground and a gaussian distribution of current density with 240 km standard deviation. With these both problem solutions we can determinate, by a vectorial sum of the fields, the geomagnetic response of a 2-D heterogeneity that has any strike orientation. Afterwards, we can obtain, with two fields polarization, the impedance tensor and show the profiles for phase and resistivity.

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