MT modeling of a 2-D structure perpendicular to the Equatorial Electrojet

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Abstract

The magnetotelluric method (MT) for the determination of subsurface electrical conductivity is based on the assumption that the incident field is laterally uniform and it is considered as plane waves. In the mid latitudes this hypothesis is valid and MT response depends only on the electrical structure of the earth. In equatorial latitudes, the geomagnetic fields shows an strong enhancement associated with electrical currents located in the ionosphere above the magnetic equator, termed Equatorial Electrojet (EEJ), which can make the primary fields nonuniform. These currents present flow reversions, therefore denominated Counter-Electrojet (CEJ). We present in this work the influence that a 2-D structure perpendicular to the EEJ would cause on the MT soundings. In this situation, we evaluated the coupled TE and TM modes using the finite element method and we employed three gaussian distributions to model the EEJ and its return currents, as well as the CEJ. The results are shown as MT soundings located in three stations crossing the 2-D structure. We noted that the components of the geomagnetic field, used to evaluate the impedance, have an influence from the coupling factor. Moreover, this influence became greater with decreasing of the frequency. For lower frequencies, about 10−4 Hz, we detect two kinds of perturbations on the MT data with respect to the plane-wave one: the first is due the presence of the 2-D source (EEJ and CEJ) as primary field, which violates the plane-wave hypothesis; and the second is caused by the coupled TE and TM modes.

Introduction

The magnetotelluric sounding method (MT) for the determination of subsurface electrical conductivity profiles as proposed by Tikhonov (1950) and Cagniard (1953) is based on the assumption that the incident electromagnetic field is laterally uniform and it is usually considered as plane waves. In the mid latitudes this hypothesis is perfectly valid and its validity implies that MT response depend only on the electrical structure of the earth. However, in equatorial latitudes, the geomagnetic fields shows an strong enhancement associated with electrical currents in a narrow strip located in the ionosphere above the magnetic equator, termed Equatorial Electrojet (EEJ), which can made the primary fields nonuniform. Occasionally these currents present flow reversions, therefore denominated Counter-Electrojet (CEJ).

Because the plane-wave hypothesis may not be applicable in the equatorial regions, several authors have studied the source effects on MT response due an 1-D and 2-D conductive geological structure underneath, in continental regions. Hermance & Peltier (1970) used an infinite line current in the eastward direction, localized at 110 km above the earth's surface, to model 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 EEJ 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) investigated the influence of EEJ on the MT data of 2-D structures, with the uncoupled TE and TM modes, and 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. Vassal *et al.* (1998) considered a gaussian model of EEJ and computed apparent resistivity for a sedimentary basin and a cratonic shield corresponding to tectonic provinces in Mali and Ivory Coast. Their numerical results confirm the observational existence of a daytime source effect related to the EEJ. Silva & Rijo (2003) applied the finite element method to evaluate numerically the geoelectromagnetic response of 2-D structure perpendicular to the electrojet in eastward direction.

We present in this work the influence that a 2-D structure perpendicular to the EEJ would cause on the classical MT response. In this situation, we evaluated the coupled TE and TM modes using the finite element method and we employed three gaussian distributions to model the EEJ and its return currents, as well as the CEJ. The results are shown as MT soundings located in three stations crossing the 2-D structure.

Methodology

As the electromagnetic theory shows, the fields associated to a source current following a planar gaussian distribution of density of 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 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 (Silva & Rijo, 2003).

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. Hence we use a match of three gaussians to model the EEJ and its return currents according to the parameters showed in Rigoti *et al.*(1999). In the Figure 1 we have the EEj and CEJ with its landmarks for our model.

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

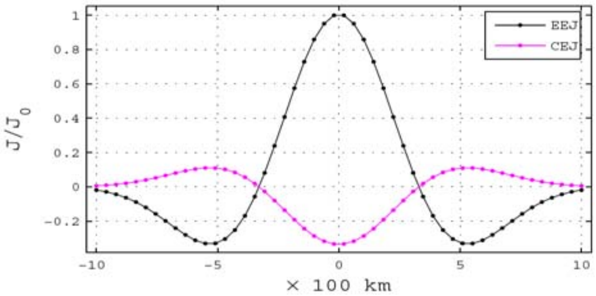


Figure 1 – Density current for the EEJ and CEJ (and its currents return) formed by three gaussians distribution.

The primary electrical field is given by the stratified media response (Ward & Hohmann, 1988). The integrals associated with the primary field components and Inverse Fourier Transform of FEM results were calculated by the linear digital filter technique (Rijo & Almeida, 2003).

According to the Maxwell's equations in the k_y spatial Fourier domain, the secondary coupled fields $\hat{H}_y^s$ and $\hat{E}_y^s$ 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:

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

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

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 interpretative model of Parnaíba Basin Conductivity Anomaly (Arora *et al.*,1997) shown in Figure 2 to investigate the effects of the EEJ/CEJ on the MT data. 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.

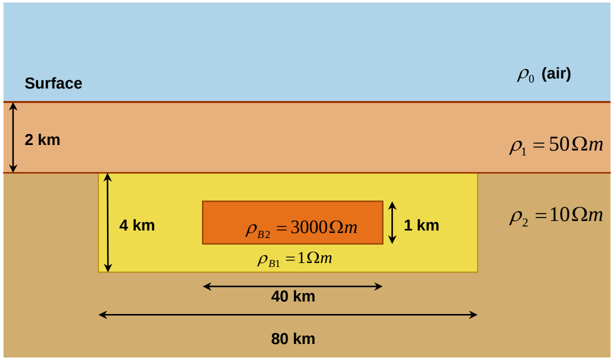
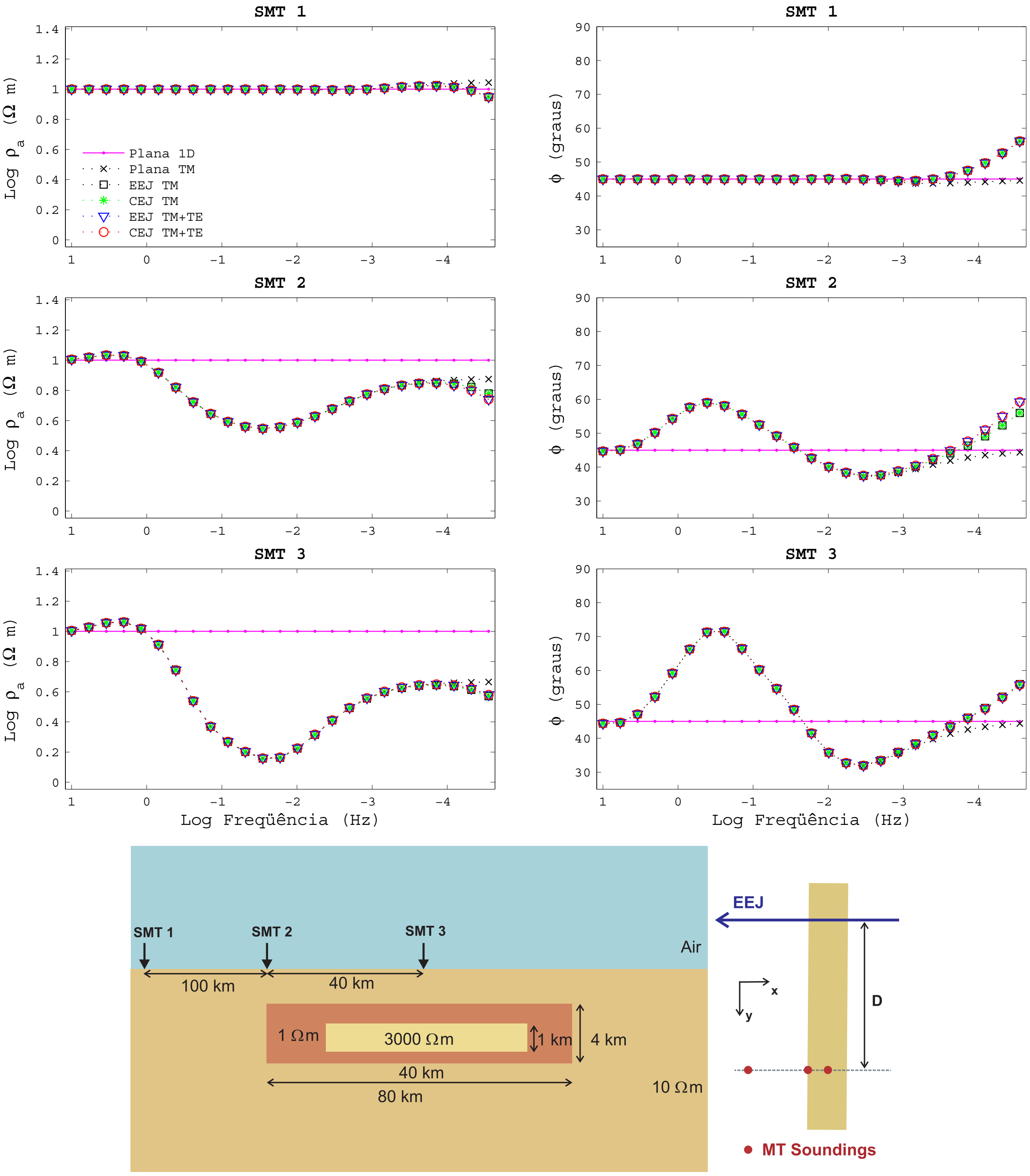


Figure 2 – Model of Parnaíba Basin Conductivity Anomaly.

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

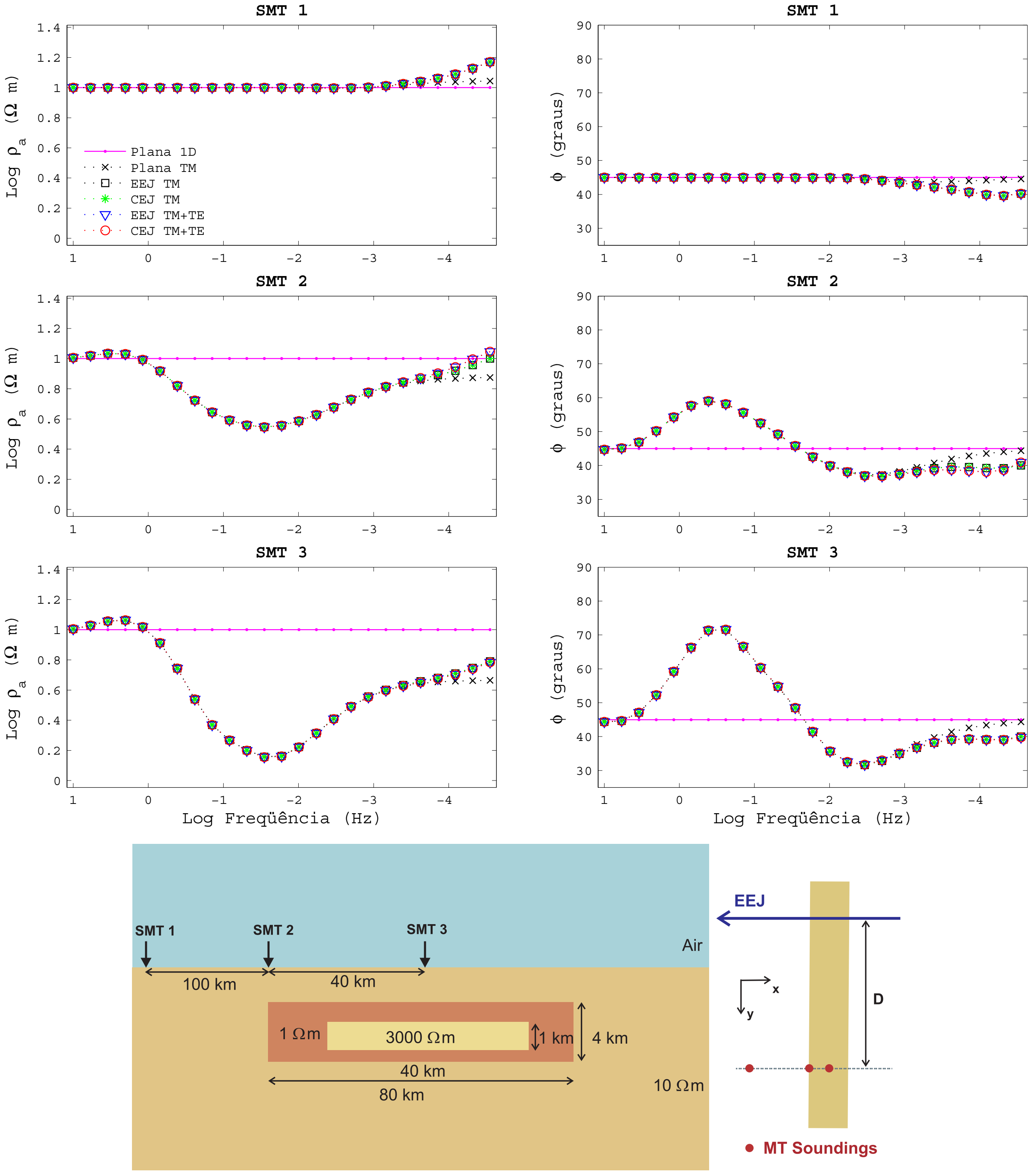
We realized ours experiments with three planar gaussians distribution of density current, resulting in an EEJ/CEJ with returns current. The center of the EEJ is located at y = 0 km. The position for MT soundings is located at 100 and 500 km from the source center. We present them in three stations, computed at the surface for the frequencies 10^1 until $10^{-4.5}$ Hz. In the figures we compare our results against the classical plane-wave response and the Mota & Rijo results, who computed the uncoupled TM mode. We include is well the 1-D MT data to stress the 2-D heterogeneity influence.



Vertical view

Plain view

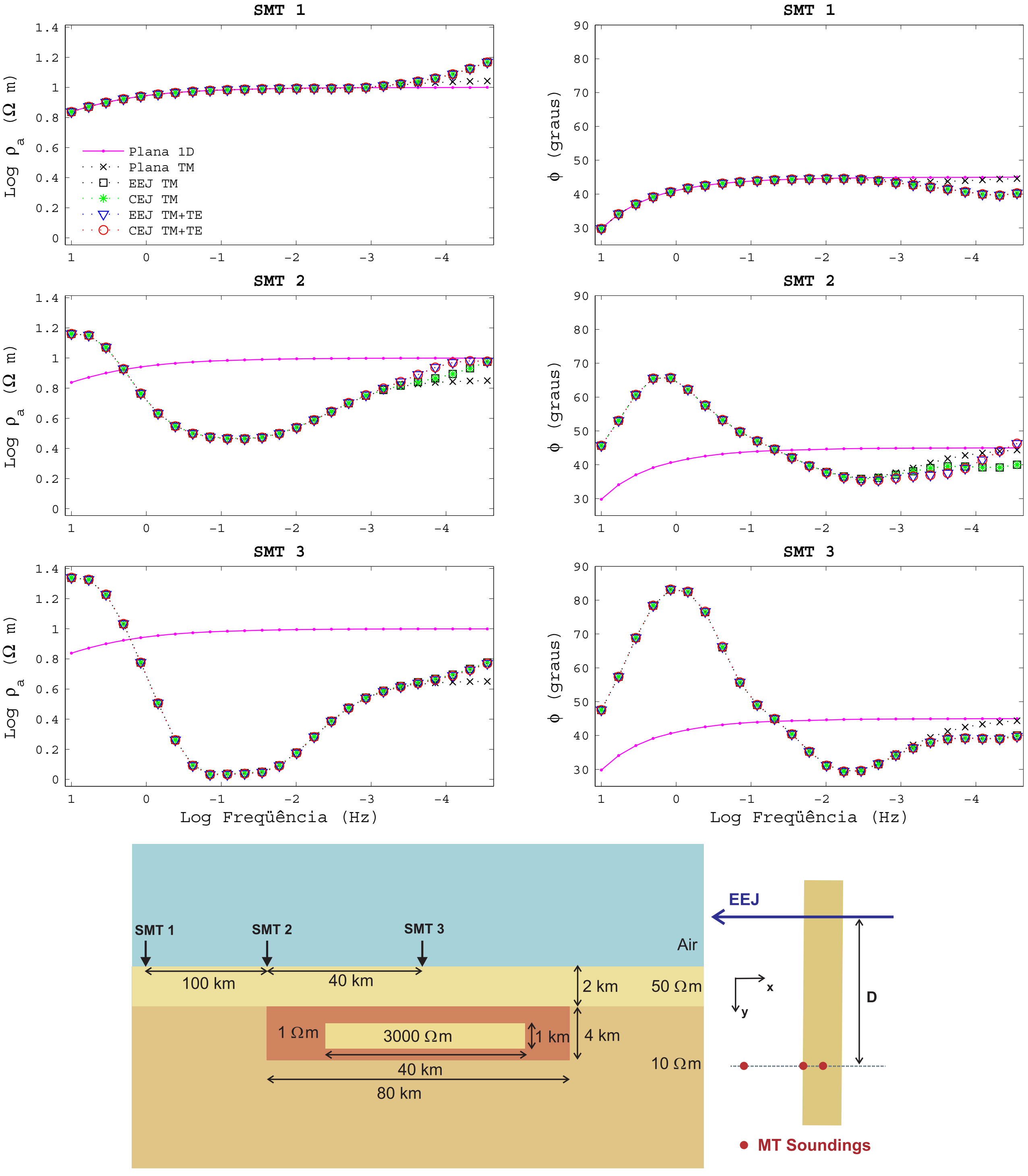
Figure 3 – MT soundings calculated under EEJ and CEJ at 100 km from the source center.



Vertical view

Plain view

Figure 4 – MT soundings calculated under EEJ and CEJ at 500 km from the source center.



Vertical view

Plain view

Figure 6 – MT soundings calculated under EEJ and CEJ at 500 km from the source center.

The amplitude and phase of the surface impedance computed at stations SMT1, SMT2 and SMT3 are shown in Figures 3, 4 and 5, where the interpretative model is depicted. In the Figure 3, we adopted a homogeneous semi-space and we observe at station SMT1 only the EEJ/CEJ influences over the plane-wave response at smaller frequencies caused by the source geometry. On the station SMT2 there is the 2-D anomaly in the response and a small divergence between coupled and uncoupled results, mainly in the phase. For the SMT3 we note a strong 2-D effect, which occur in the amplitude but not in the phase, even for plane-wave.

In the Figure 4 we have the same model but the soundings are located at 500 km from the EEJ center. As consequence, the values of 2-D source are unlike of plane-wave ones, for higher values in resistivity and smaller values in phase. Possibly these inversions are due to the returns current of EEJ/CEJ. At 500 km from the source, the coupling influences are lesser, as could see in the sounding SMT2. Again, there is the 2-D effect in the SMT3 resistivity, but in minor amplitude.

Finally in the Figure 5 we include a 50 Ωm first layer to model the Parnaíba Basin Conductive Anomaly. Comparing with Figure 4, we note the influence of the semi-space on the 1-D data but the source effect is the same on the STM1. For the STM2 there is a higher difference in the coupled results, mainly in phase since 10^{-3} Hz. In the SMT3 we observe, comparing with Figure 4, only the anomaly caused by the first layer.

In all our experiments there are not influences due the amplitude of the incident fields, therefore the soundings of EEJ and CEJ are identical. Its important to observe the divergence caused by the coupled TE and TM modes at smaller frequencies

Conclusions

We present in this work the influence that a 2-D structure perpendicular to the EEJ would cause on the MT soundings. We used the EEJ and CEJ as primary source and we compared our results with the plane wave response. We noted that the components of the geomagnetic field, used to evaluate the impedance, have an influence from the coupling factor between the TE and TM modes. Moreover, this influence became greater with decreasing of the frequency. However, the coupling factor do not affects the MT response at frequencies higher than 10^{-2} Hz. For lower frequencies, about 10^{-4} Hz, we detect two kinds of perturbations on the MT data with respect to the plane-wave one: the first is due the presence of the 2-D source (EEJ and CEJ) as primary field, which violates the plane-wave hypothesis; and the second is caused by the coupled TE and TM modes.

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