“Magnetic statics” shift effects on 2-D TE Magnetotelluric soundings

Luiz Rijo (rijo@amazon.com.br) UFPA, Brasil

Abstract

It is well know among Magnetotelluric practitioners the appearance of a parallel dislocation of MT mode apparent resistivity curves produced by conductive 2-D and 3-D shallow structures. This phenomenon is known as “*statics” shift effects.* In the resistive host side, the shift is upward and in the conductive inhomogeneity side the shift is downward. The shift is observed over the full frequency (period) range. The phase of the impedance curves does not show such phenomenon. Conductive shallow inhomogeneities do not cause “statics” shift on TE mode curves. However, magnetic permeable shallow inhomogeneities do produce a similar phenomenon on TE mode apparent resistivity curves. In order to distinguish this case from the classic conductive “statics” shift we nominated it “magnetic statics” shift. In this paper, both types of “statics” shifts are shown through many typical examples.

Introduction

It is well know among Magnetotelluric practitioners the appearance of a parallel dislocation of MT mode apparent resistivity curves produced by conductive 2-D and 3-D shallow structures (Orange, 1981). This phenomenon knowing as “*statics” shift effects* is observed on TM mode sounding curves obtained in the vicinity of the contact between a conductive shallow inhomogeneity and the host. These effects are observed over the full frequency (period) range. The TM mode phase curves are not affected by this phenomenon. Likewise, the TE Mode apparent resistivity and phase curves do not show “statics” shift effects produced by conductive outcrops. On the other hand, shallow magnetic permeable structure do creates similar effects on TE Mode apparent resistivity curves. Our aim in this paper is to explain this phenomenon on TE Mode apparent resistivity curves.

Methodology

The results we are about to show were carried out numerically by the finite elements method. Thus, we start with Maxwell’s equations on frequency domain for the secondary fields $\mathbf{E}^s$ and $\mathbf{H}^s$,

$$\nabla\times\mathbf{H}^s - \sigma\mathbf{E}^s = \Delta\sigma\mathbf{E}^p,$$

$$\nabla\times\mathbf{E}^s + i\omega\mu\mathbf{H}^s = -i\omega\Delta\mu\mathbf{H}^p,$$

where $\mathbf{E}^p$ and $\mathbf{H}^p$ are the layered earth primary electric and magnetic fields within the inhomogeneity. The contrast of the conductivity and permeability between the inhomogeneity and the host are given by $\Delta\sigma$ and $\Delta\mu$, respectively.

Applying Galerkin finite elements strategy on these Maxwell’s equations we find for the

TM Mode,

$$\int_{\partial\Omega_e}\frac{1}{\sigma}\left(\frac{\partial\psi_m}{\partial x}\frac{\partial H_y^s}{\partial x}+\frac{\partial\psi_m}{\partial z}\frac{\partial H_y^s}{\partial z}\right)dxdz + i\omega\int_{\Omega_e}\mu\psi_m H_y^s dxdz$$
$$= -i\omega\int_{\Omega_e}\Delta\mu\psi_m H_y^p dxdz + \int_{\Omega_e}\frac{\Delta\sigma}{\sigma}\left(\frac{\partial\psi_m}{\partial x}E_z^p - \frac{\partial\psi_m}{\partial z}E_x^p\right)dxdz$$
$$+\int_{\partial\Omega_e}\psi_m\mathbf{E}^s\cdot\hat{\mathbf{t}}dl, \qquad m = 1, 2 \cdots \mathrm{N} \qquad (1)$$

and for the

TE Mode,

$$\int_{\partial\Omega_e}\frac{1}{i\omega\mu}\left(\frac{\partial\psi_m}{\partial x}\frac{\partial E_y^s}{\partial x}+\frac{\partial\psi_m}{\partial z}\frac{\partial E_y^s}{\partial z}\right)dxdz + \int_{\Omega_e}\sigma\psi_m E_y^s dxdz$$
$$= -\int_{\Omega_e}\Delta\sigma\psi_m E_y^p dxdz - \int_{\Omega_e}\frac{\Delta\mu}{\mu}\left(\frac{\partial\psi_m}{\partial x}H_z^p - \frac{\partial\psi_m}{\partial z}H_x^p\right)dxdz$$
$$+\int_{\partial\Omega_e}\psi_m\mathbf{H}^s\cdot\hat{\mathbf{t}}dl, \qquad m = 1, 2 \cdots \mathrm{N} \qquad (2)$$

where ψ_m are the basis functions on the element Ω_e. The unit vector $\hat{\mathbf{t}}$ is tangential to the boundary $\partial\Omega_e$ of the element Ω_e. N = 3 for triangular elements, N = 4 for quadrilateral elements and N = 8 for isoperimetric elements (Rijo, 1977).

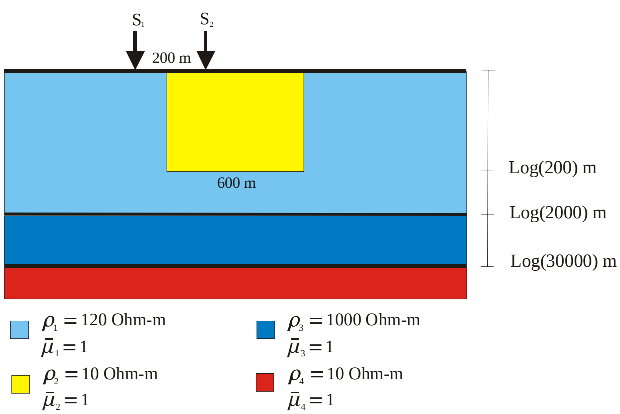
The equations (1) and (2) are the fundamental equations for the finite elements 2-D Magnetotelluric forward modeling. Observe the beautiful symmetry between these two equations. It is precisely this electromagnetic duality that explains the “statics” shift effects on both TM and TE modes. The second integral of the right side of equation (1) is the term responsible for the “statics” shift effect on the TM mode apparent resistivity curves. Likewise, the second integral of the right side of the equation (2) is the source of the “statics” shift effects on the TE mode apparent resistivity curves. We see from these equations that for the TM mode case, the "statics" shift effects are caused by the contrast of conductivity (or resistivity), whereas in the TE mode case is the contrast of the magnetic permeability that creates the "statics" shift on the TE mode apparent resistivity curves. Thus, if the media are no permeable there is no "statics" shift effect on the TE mode data. The next examples illustrate what we have just said.

.

The models and examples

The studied models are a three layers earth with an outcropped shallow inhomogeneity. The first layer represents a 2000 m thick sedimentary basin with120 ohm-m resistivity. The second layer corresponds to a 30 km 1000 ohm-m resistive crust and finally, the 10 ohm-m basement representing the conductive upper mantle. The shallow 2-D inhomogeneity is a 600 m long and 200 m thick tabular body, which may be thought as a thin discontinuous alluvial-filled depression. Four models will be considered. The first model is the basic model where all three layers and the shallow inhomogeneity are no permeable. In the second model the relative permeability of the outcropped body is equal to 5. In the third model the relative permeability of the first layer is equal to 2.5. The combination of second and third models forms the last model. Two MT soundings 200 m apart, one at each side of the inhomogeneity supply the data for the analysis..

Model 1



The Figure 1a shows the comparison of the 1-D (layered earth beneath the MT sounding S1) apparent resistivity curve with the TE (red line) and TM 2-D (blue line) curves to the left of the inhomogeneity. The 1-D and TM 2-D curves are nearly identical except for the parallel dislocation upward, characterizing the "statics" shift effect. The TE mode curve is practically identical with 1-D curve except for the lowered periods. The curves of the phase of impedance (Figure 1b) are virtually identical to the 1-D curve except for the lowest periods where the effect of the presence of the shallow 2-D body is more pronounced.

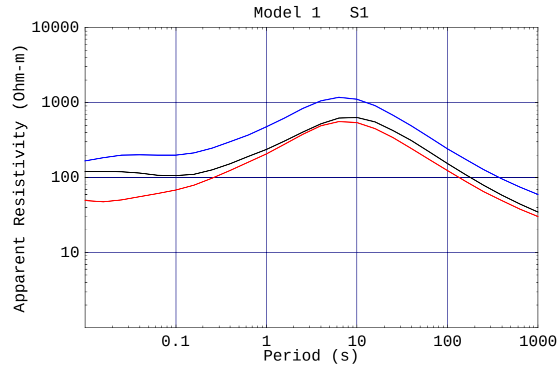


Figure 1a. Model 1: apparent resistivity curves outside of the inhomogeneity (S1). TM - blue, TE – red and 1D – black.

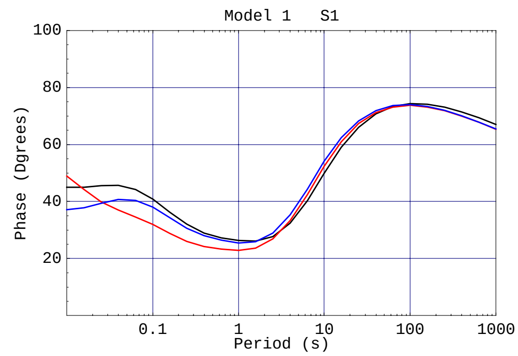


Figure 1b. Model 1: curve of the phase of the impedance outside of the inhomogeneity (S1). TM - blue, TE – red and 1D – black.

On the conductive side of the contact the "statics" effect on the TM apparent resistivity curve (blue line) is very pronounced (Figure 2a). Note that it is dislocated downward and keeps parallel to the 1-D curves at the highest periods. No similar effect is observed on the TE mode curve at the same figure..

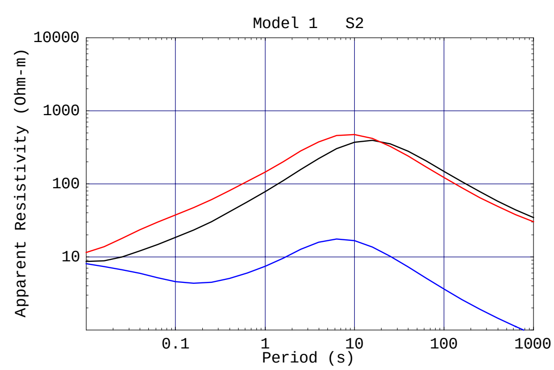


Figure 2a. Model 1: apparent resistivity curves inside of the inhomogeneity (S2). TM - blue, TE – red and 1D – black.

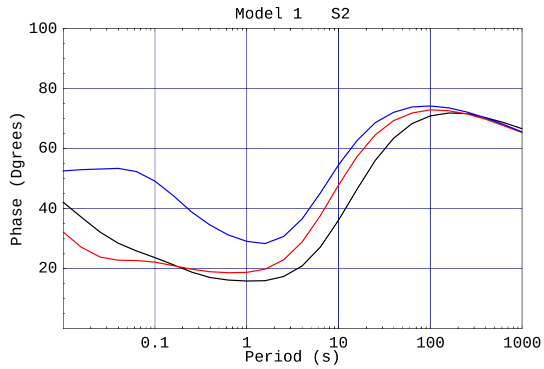
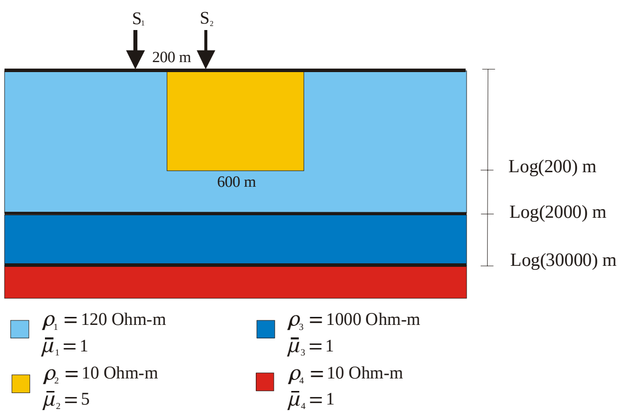


Figure 2b. Model 1: curve of the phase of the impedance inside of the inhomogeneity (S2). TM - blue, TE – red and 1D – black.

The curves of the phase of the impedance (Figure 2b) do not show any "statics" shift effects. The difference observed among the three curves at lower periods is simply the pure response of the shallow inhomogeneity.

Model 2



The model 2 is the same geometry as that of model 1, but with a magnetic (relative permeability $\bar{\mu}_2 = \mu_2 / \mu_0 = 5$) inhomogeneity.

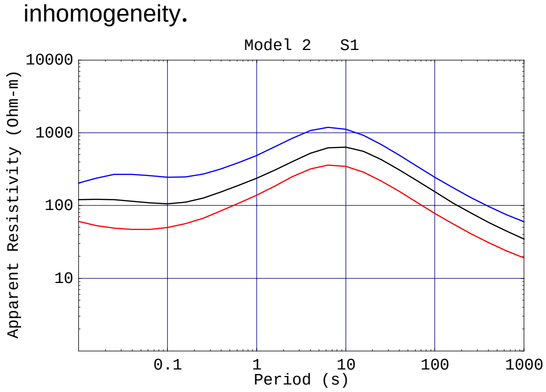


Figure 3a. Model 2: apparent resistivity curves outside of the inhomogeneity (S1). TM - blue, TE – red and 1D – black.

In the Figure 3a we observe the "statics" effects on both apparent resistivity curves of the left side sounding (S1). The conductive (traditional) TM mode "statics" shift and the magnetic TE mode "statics" shift caused by the discontinuity of values of the magnetic permeability between the host and the body.

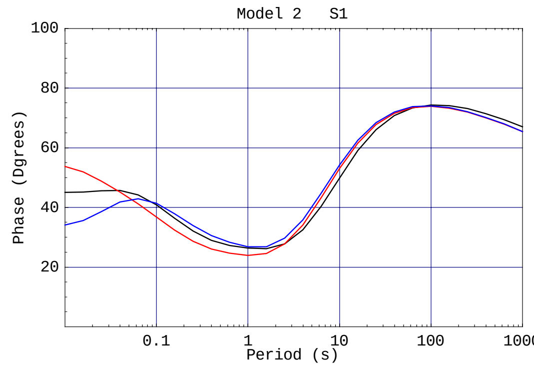


Figure 3b. Model 2: curve of the phase of the impedance outside of the inhomogeneity (S1). TM - blue, TE – red and 1D – black.

No "statics" effects are observed on the curves of the phase of the impedance (Figure 3b).

On the right side, above the conductive and permeable body (S2) the "statics" effects are more preeminent (Figure 4a).

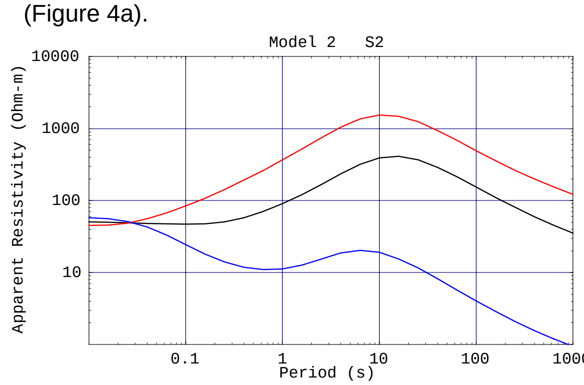


Figure 4a. Model 2: apparent resistivity curves inside of the inhomogeneity (S2). TM - blue, TE – red and 1D – black.

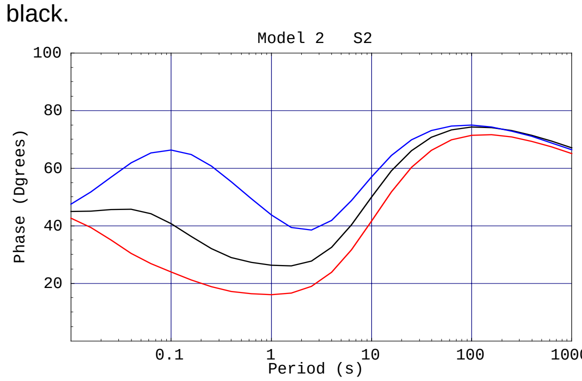
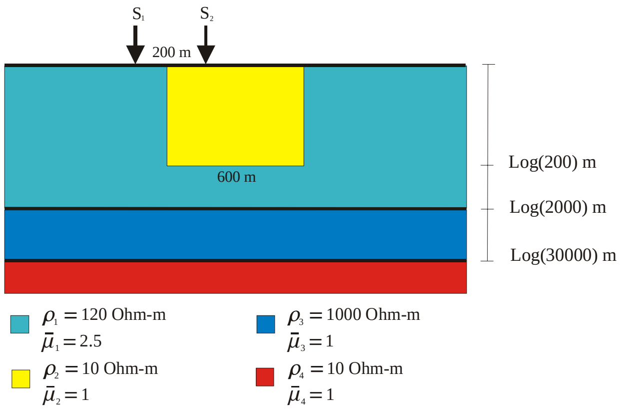


Figure 4b. Model 2: curve of the phase of the impedance inside of the inhomogeneity (S2). TM - blue, TE – red and 1D – black

.Model 3



The model 3 is the same geometry as that of model 1, but with a magnetic (relative permeability $\bar{\mu}_1 = \mu_1 / \mu_0 = 2.5$) first layer. The inhomogeneity is no permeable.

The “statics” shift of the apparent resistivity TM curve at the left side (Figure 5a) decreased slightly but is still present. No “statics” effect is observed on the TE curve.

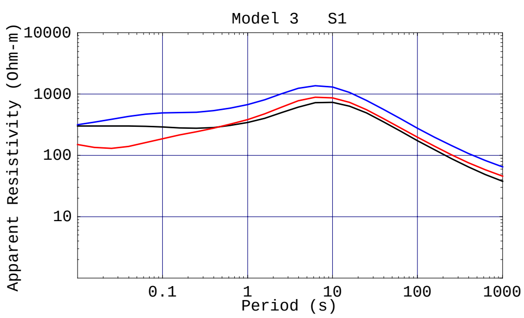


Figure 5a. Model 3: apparent resistivity curves outside of the inhomogeneity (S1). TM - blue, TE – red and 1D – black.

As usual, the curves of the phase of impedance do not change at highest periods (Figure 5b).

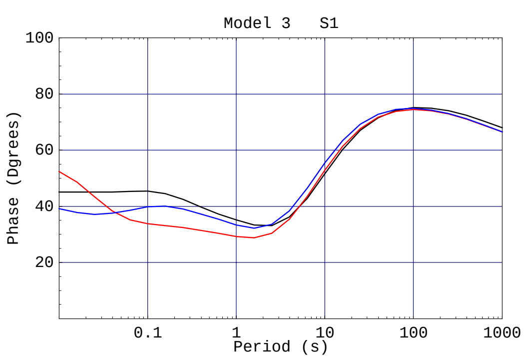


Figure 5b. Model 3: curve of the phase of the impedance outside of the inhomogeneity (S1). TM - blue, TE – red and 1D – black

At the right side of the contact with the inhomogeneity the curves of the Figures 6a and 6b behaves as expected.

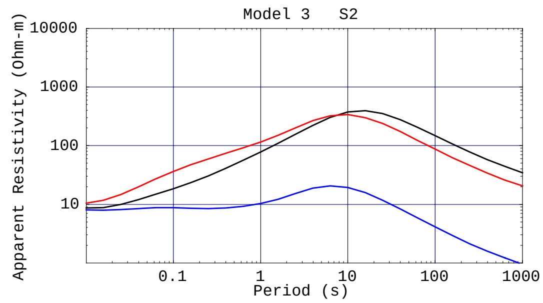


Figure 6a. Model 3: apparent resistivity curves inside of the inhomogeneity (S2). TM - blue, TE – red and 1D – black.

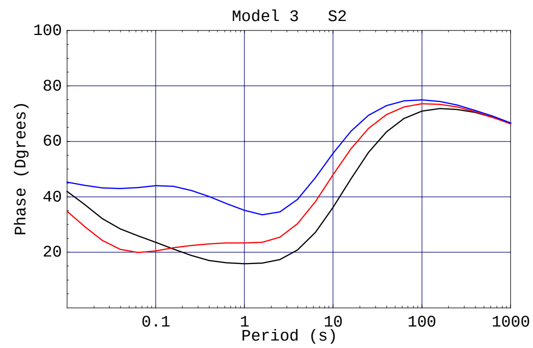
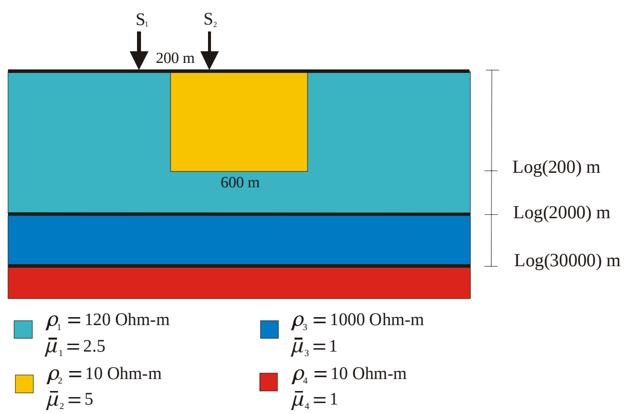


Figure 6b. Model 3: curve of the phase of the impedance inside of the inhomogeneity (S2). TM - blue, TE – red and 1D – black

Model 4



This last model is a combination of the second and third models. The inhomogeneity and the first layer are both permeable.

As expected the “statics” shift effects appear on both TM e TE apparent resistivity curves (Figure 7a and 8b).

Naturally, the curves of the phase of impedance (Figure 7b and 8b) do not exhibit any "statics" effects.

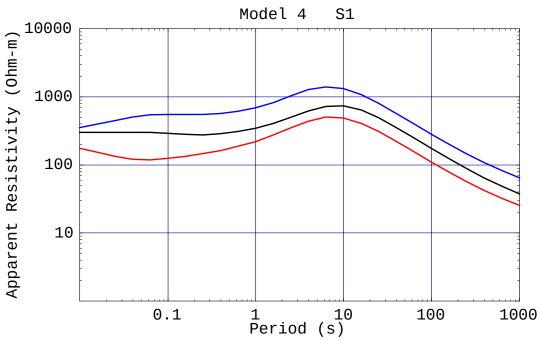


Figure 7a. Model 4: apparent resistivity curves outside of the inhomogeneity (S1). TM - blue, TE – red and 1D – black.

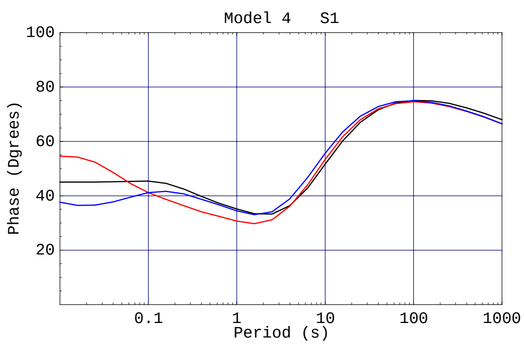


Figure 7b. Model 4: curve of the phase of the impedance outside of the inhomogeneity (S1). TM - blue, TE – red and 1D – black

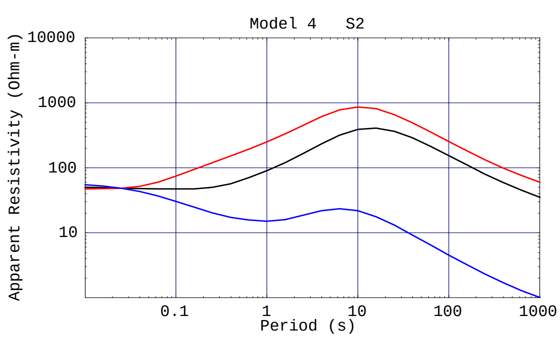


Figure 8a. Model 3: apparent resistivity curves inside of the inhomogeneity (S2). TM - blue, TE – red and 1D – black.

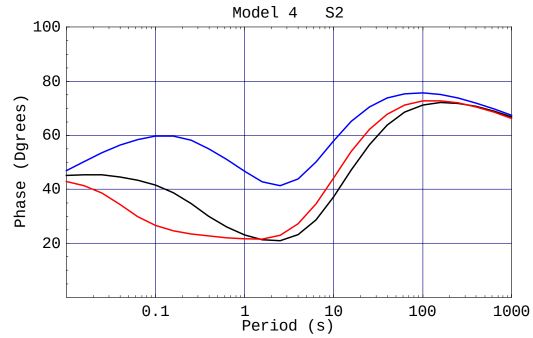


Figure 8b. Model 4: curve of the phase of the impedance inside of the inhomogeneity (S2). TM - blue, TE – red and 1D – black

Conclusions

The electromagnetic duality (conductivity ↔ magnetic permeability; magnetic field H ↔ electric field E) between the TM and TE Magnetotelluric modes justify the occurrence of a magnetic "statics" shift effect on the apparent resistivity TE curves similar to the well known conductive "statics" shift effect observed on TM mode apparent resistivity sounding curves. Low frequency electrical currents at the contact between the conductive inhomogeneity and the surrounded medium cause the conductive "statics" shift. Similarly, low frequency "magnetic" currents create the magnetic "statics" shift. Magnetic "currents" are greatly enhanced by the intensity of the permeability of the medium. The traditional "statics" effects caused by shallow conductive inhomogeneities are always present on apparent resistivity TM curves. To have similar effect on the TE mode, the inhomogeneity has to be highly permeable. Geologically, the alluvial-filled depression must have a great concentration of magnetic minerals (magnetite or ilmenite) to be able to produce a appreciable TE mode "statics" shift effect. .

Acknowledgments

We wish to thank the agencies CNPq, CAPES and ANP for funding the PROEM (Laboratory for EM processing of the Department of Geophysics - UFPA),where this work was realized.

References

Orange A. S., 1981, Notes on the interpretation of magnetotelluric data in complex areas. Report of Emerald Exploration Consultants, Inc.

Rijo L. 1877, Modeling of electric and electromagnetic data. PH.D. Thesis, University of Utah.