

Understanding of Near-field Effect for CSAMT in Electric Azimuthally Anisotropic Half-space

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Summary

This paper revised the electromagnetic fields induced by a horizontal electric dipole (HED) on the surface of a horizontal layered earth with azimuthal anisotropy. We estimate the far-field distance (FFD) of a homogeneous half-space with azimuthally anisotropy through numerical tests. We found that the FFD is linear with the skin depth if the coefficient of anisotropy is a constant. We also found the influence of anisotropy on the FFD is stronger along the strike than perpendicular to the strike and the value of the FFD is much larger along the strike than perpendicular to the strike. Therefore, before inverting Controlled Source Audio-Magneto Telluric (CSAMT) data, near-field effects must be carefully corrected. In this paper, we suggest to use far-field approximations to perform the near-field correction.

Introduction

For Controlled Source Audio-Magneto Telluric (CSAMT) exploration, near-field effect is an annoying problem and widely discussed. Generally speaking, in the near-field (separation between the transmitter and receiver less than 3 skin depth), the H-field decays at r^{-2} , becomes saturated and no longer varies as a function of frequency or resistivity. The E-field still remains a function of resistivity, decays at r^{-3} , but is independent of frequency. It is in this near-field zone that depth of investigation becomes independent of frequency and dependent upon array geometry (see Zonge and Hughes, 1991). Routh and Oldenburg (1996) developed an inverse algorithm to recover a 1D conductivity structure of the Earth from CSAMT data without applying any correction to the data before the inversion. The results from inversion were compared with the inversion of near-field corrected data using an MT inversion algorithm, and show both of synthetic and field data had significant differences in the conductivity models. Therefore they suggested that it is prudent to carry out complete inversion as opposed to inverting near-field corrected data. Moreover, they did not focus on this problem in anisotropy media. Li and Pedersen (1991) deduced CSAMT responses of a layered earth with azimuthal anisotropy. However, they did not make further investigation of the near-field effect.

This paper studies the near-field effect of an azimuthally anisotropic half-space, which is in hope of understanding the distortion of the far-field distance (FFD) caused by azimuthal anisotropy and performing CSAMT in such circumstances.

Theory

Assuming a layered earth consists of N azimuthally anisotropic layers. The XY-plane parallels to the ground surface, and the X axis towards the strike direction. The Z axis is vertical, and Z equals to zero on the ground surface. In the m -th layer, conductivity tensor has the form:

$$\boldsymbol{\sigma}_m = \begin{bmatrix} \sigma_{mt} & 0 & 0 \\ 0 & \sigma_{mn} & 0 \\ 0 & 0 & \sigma_{mt} \end{bmatrix}, \quad (1)$$

where subscript t and n present parallel and perpendicular to the strike. The anisotropic parameter and averaging conductivity are respectively defined as: $\lambda_m = \sqrt{\sigma_{mt}/\sigma_{mn}}$, $\bar{\sigma}_m = \sqrt{\sigma_{mt}\sigma_{mn}}$.

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EM-Field time dependence is assumed to be $e^{i\omega t}$. Let subsurface permeability be equal to the vacuum permeability μ_0 .

Using a vector potential \mathbf{A}_m and a scalar potential φ_m give the electric and magnetic fields in the m -th layer as:

$$\mathbf{H}_m = \nabla \times \mathbf{A}_m, \mathbf{E}_m = -i\omega\mu_0 \mathbf{A}_m - \nabla \varphi_m. \quad (2)$$

The analytic solutions of previous equations using the horizontal electrical dipole (HED) as a source were given by Li and Pedersen (1992). The impedances of TE and TM modes on the air-earth interface can simply be calculated from the components of the electrical and magnetic field.

In order to understand the near-field effect of CSAMT, a comparison between responses of CSAMT and MT must be done. MT responses of the same model can be calculated from the following recursion formula:

$$B_N = \alpha_N, B_m = \alpha_m \frac{B_{m+1} + \alpha_m \tanh(\alpha_m h_m)}{\alpha_m + B_{m+1} \tanh(\alpha_m h_m)}, m = N-1, \dots, 2, 1. \quad (3)$$

$$\text{For TE mode: } \alpha_m = \sqrt{i\omega\mu_0\sigma_{mt}}, m = N, \dots, 2, 1; \text{ on the earth surface, } Z_{TE} = i\omega\mu_0/B_1, \quad (4)$$

$$\text{For TM mode: } \alpha_m = \sqrt{i\omega\mu_0\sigma_{mn}}, m = N, \dots, 2, 1; \text{ on the earth surface, } Z_{TM} = -i\omega\mu_0/B_1, \quad (5)$$

Modeling Results

In following numerical tests, the HED was chosen as a field source for CSAMT, and observations were made on the surface of the earth with an azimuthally anisotropic half-space. The responses of CSAMT were calculated using Li and Pedersen's method (1992). The responses of MT were calculated using formulae (3), (4), and (5). The dipole is located at (0, 0, 0), and its direction is along the x axis, e.g., parallels to strike. The moment of HED is 1 Am, and $\sigma_t = 0.01$. The spatial resolution is 0.1 meter in the following figures. For the chosen coordinate system the resistivity ρ_{xy} equals to ρ_{TE} , and ρ_{yx} equals to ρ_{TM} . The FFD is defined between the transmitter and the observation point, which relative difference of theoretical apparent conductivity

between CSAMT and MT is less than 5%, e.g., $\eta_1 = \left| \frac{\rho_{xy} - \rho_{TE}}{\rho_{xy}} \right| \leq 5\%$, $\eta_2 = \left| \frac{\rho_{yx} - \rho_{TM}}{\rho_{yx}} \right| \leq 5\%$, where ρ_{xy} and ρ_{TE} were calculated from responses of CSAMT and MT respectively.

Figure 1 is a diagram of the FFD vs. azimuthal angle for $\lambda = 1, 1.5, \text{ and } 2.0$, respectively. In green areas the relative difference η_1 of theoretical apparent conductivity between CSAMT and MT is less than 5%, and therefore can be realized as far-field domain. It shows a not simple structure compared with the isotropic half-space. Obviously, the area of the near field becomes a flower shape when $\lambda > 1$, and the FFD in the strike direction is larger than that in its orthogonal direction when λ approaches two. By inspection of the FFD_x vs. ρ_t for different frequencies at a middle degree of anisotropy $\lambda = 1.5$, referring to Figure 2, we found $FFD_x = 10^{A(f)} * \rho_t^{0.5}$, and $A(f) = 3.455 - 0.500 \log_{10}(f)$. If we set the skin depth

$\delta_x \approx 503.29 \sqrt{\frac{\rho_t}{f}}$ along the strike direction, then in theory $FFD_x = 5.665 \delta_x$. This means the FFD must exceed 5.665 times

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the skin depth in a half-space with a middle degree of azimuthally anisotropy if we make measurements along the strike direction.

There are two questions arising from previous analysis. How does the FFD_x/δ_x change with λ ? Are the changes the same in the X and Y directions? Now let us refer to Figure 3 and Figure 4. In the case of the FFD is defined by setting $\eta_1 < 5\%$, in the Y direction the FFD_y/δ_x is approximately linear increasing with λ when $1.2 < \lambda < 2$. On the other hand the FFD_x/δ_x vs. λ shows a complex shape.

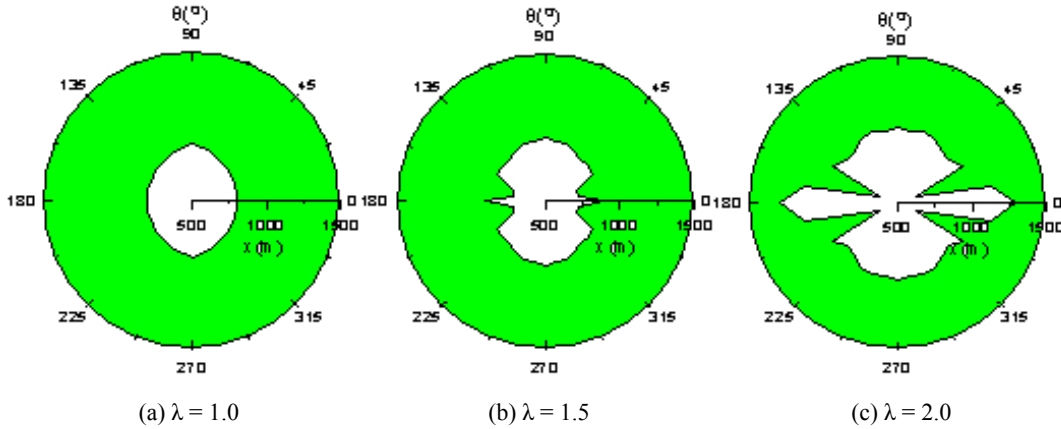


Figure 1. Diagrams of FFD vs. azimuthal angle for different anisotropic parameters at frequency 1,000Hz.

In the case of the FFD is defined by setting $\eta_2 < 5\%$, the FFD_x/δ_x is approximately linear increasing with λ in the common interval, however the FFD_y/δ_x vs. λ shows a smooth curve. From comprehensive analysis it is obviously concluded that when the

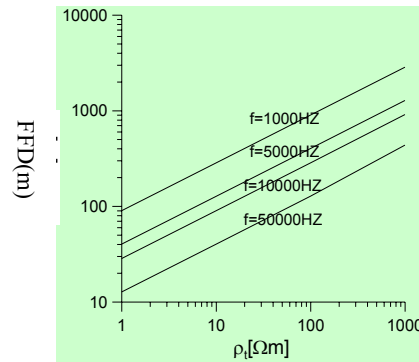


Figure 2. Diagram of FFD(x) vs. ρ_1 for changing frequency when $\lambda = 1.5$ (the HED direction parallels to the strike).

measurement is carried out along the x-direction the FFD is well-defined by η_2 , on the contrary when the measurement is carried out along the y-direction the FFD is well-defined by η_1 . This should be a valuable rule to perform CSAMT in practice.

Conclusion

The FFD of CSAMT is more complex in an azimuthally anisotropy half-space than in the homogeneous half-space. The FFD has a determining relationship between the earth resistivity and a working frequency. In practice, the FFD along a strike

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direction should be estimated by comparing the relative difference between responses of CSAMT and MT in the TM-mode and the FFD along the direction perpendicular to the strike should be estimated by comparing relative difference between responses of CSAMT and MT in the TE-mode.

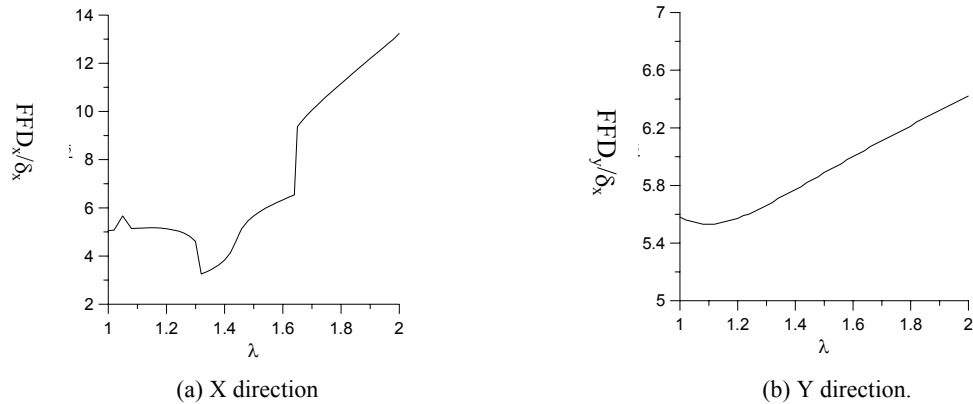


Figure 3. Illustration of FFD/δ_x vs. λ when $\eta_1 < 5\%$.

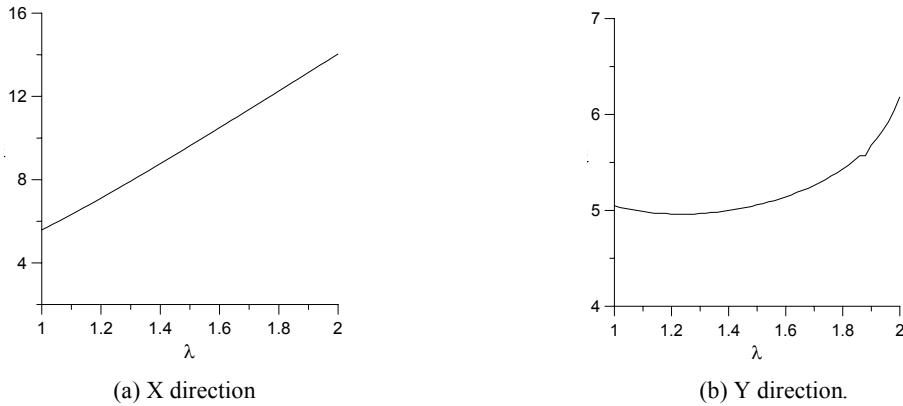


Figure 4. Illustration of FFD/δ_x vs. λ when $\eta_2 < 5\%$.

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