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A resolution comparison of horizontal and vertical magnetic transfer functions

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Abstract

The main goal of the present study is to identify characteristics of the inter-station horizontal magnetic responses and the vertical magnetic data, as two types of magnetotelluric transfer functions, in the modeling procedure. Through consideration of model responses and two-dimensional inversion of synthetic data, sensitivity of the data components in detecting different geophysical structures is investigated. An inversion of the magnetic transfer functions related to a real data set has been also accomplished, and the importance of a reference selection in analysis of the inter-station horizontal magnetic data has proved. Analysis of the results of the synthetic tests confirms the efficiency of the modeling based on horizontal magnetic responses and indicates more accuracy of this type of data, especially in terms of the resolution of the deep targets. There is not a great difference in the resolution of the structures between two datasets, as closely located anomalies are examined. Furthermore, both transfer functions can also sense vertical conductivity distribution.

Keywords: Magnetotelluric transfer functions, Two-dimensional inversion, Electrical conductivity

1 Introduction

Magnetotellurics, as a passive exploration method, has been widely used to determine electrical conductivity distribution of the Earth. Only local transfer functions, namely impedance tensor and tipper data are usually analyzed and inverted in the modeling procedure. The aim of the present study is to incorporate magnetovariational responses into the set of transfer functions and to characterize their main properties. These responses were introduced by Schmucker (1970); however, their usage in electromagnetic exploration has become common only in recent years (Sokolova and Nayran, 2004; Soyer and Brasse, 2001; Varentsov, 2007a and 2007b). Inter-station horizontal magnetic data have two important advantages: they are free from galvanic distortions; and show maximum values above centers of conductive anomalies (Varentsov and EMTESZ-Pomerania Working Group, 2005).

The properties of Transverse Electric (TE) and Transverse Magnetic (TM) modes and to some extent the tipper data and their sensitivities to shallow and deep, resistive and conductive structures and three-dimensional effects have been extensively studied (Becken et al., 2008; Berdichevsky et al., 1984; Ledo et al., 2002; Siripunvaraporn et al., 2005; Wannamaker, 1999). According to these studies, TM-mode inversion reflects one-dimensional background and has high sensitivity to resistive structures. In contrast, TE can sense local conductive anomalies and is more reliable for detecting deep targets. Tipper is particularly influenced by small-scale inhomogeneities.

Considering the magnetovariational responses as part of transfer functions, they can be compared to tipper data in terms of the resolution characteristics. To obtain a proper resistivity model, we need to use impedance data. Tipper and magnetovariational responses- vertical and horizontal magnetic transfer functions- are not very effective for detecting regional and layered structure and more important for inferring lateral

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conductivity changes. Considering theoretical responses and inversion results obtained from some synthetic models, properties of these two types of magnetic transfer functions are examined.

The paper is organized in the following way. Section 2 introduces MT and MV transfer functions. Three synthetic models used in the present study are described in Section 3, while results of the analysis of synthetic models are expressed in Section 4,. A discussion and conclusions are presented in section 5.

2 MT and MV transfer functions

In magnetotelluric method, fluctuations of the natural electromagnetic field, utilized as the source, induce electrical currents into the Earth. The relationships between the resulting electromagnetic field components, measured on the Earth's surface, are functions of electrical conductivity of the subsurface and frequency.

The above mentioned relationships are expressed as transfer functions and in the standard MT, they include local impedance tensor [Z] and tipper [W]:

$$E = ZH \tag{1}$$

$$H_z = W_x H_x + W_y H_y \tag{2}$$

in which E and H represent electric and magnetic fields, respectively. Impedance is usually displayed via two parameters, apparent resistivity and phase (ρ_a, φ):

$$\rho_a = \frac{1}{\mu_0 \omega} |Z|, \tag{3}$$

$$\varphi = \tan^{-1} \left\{ \frac{Re(Z)}{Im(Z)} \right\} \tag{4}$$

The ensemble of transfer functions can be extended by calculation of the inter-station horizontal magnetic tensor or magnetovariational responses [M^a] that represents linear relationship between the horizontal magnetic fields of two sites:

$$H(r) = M(r,r_0)\, H(r_0), \tag{5}$$

where r is the local or observation site and r_0 the base or reference one. The base site is situated on a normal section of the surveyed area. The inter-station horizontal magnetic transfer functions can be obtained from simultaneously operating stations and need multi-site data processing techniques.

In two-dimensional (2D) case, assuming x-axis as the strike direction, the complete set of data components are the following: apparent resistivities and phases for both polarizations, real and imaginary parts of tipper and real and imaginary parts of inter-station magnetic tensor. However, we restrict our study to the investigation of the effects of using magnetovariational responses as an independent data set and their comparison to the tipper.

3 Synthetic models

We have considered three different synthetic models to study the depth and lateral resolution and sensitivity to vertical conductivity distribution or layered structure for both horizontal and vertical magnetic data. Magnetic responses corresponding to 27 stations along a 300-km profile for 11 periods in the range of [10,20000s] have been used to create synthetic data set. Gaussian noise equal to two percent was added to the data prepared for the inversion. For the 2D inversion, we used the REBOCC code (Siripunvaraporn and Egbert, 2000), modified by Soyer (2002) to include the inversion of magnteovariational data. In this algorithm, the smoothest model which fits the data is sought. A 100 ohm.m homogenous half-space was selected as a starting model for all inversions.

3-1 Depth resolution

The first synthetic model consists of a layer with a resistivity of 1 ohm-m and a thickness of 4 km at the center of the profile. This layer acts as an overburden. Two blocks of 25 x 25 km^2 with a 1 ohm-m resistivity are also located along the profile at different depths of 15 km and 35 km (Figure 1-a). Real and imaginary parts of the inter-station magnetic data and tipper generated from the model for two characteristic stations above the conductive blocks are shown in Figure 1-b. The amplitude of changes in case of MV data is larger than tipper. The conductive overburden significantly affects the obtained resolution at greater depths. Figure 1-c shows the same for the case without overburden. Comparison of the plots reveals weakening of the responses due to the conductive cover, and an increase of the depth for the tipper.

More details as well as stability can be obtained out of the joint inversion of all 8 components of the data, including apparent resistivities and phases of two polarizations. However, only the results of separate inversions of tipper and MV data are performed and presented in Figure 2. The shallower block is almost similar in both models. Nevertheless, the resolution of the deep block in the model based on an inversion of tipper is poor, and a horizontal bias can be seen between the two blocks. Obviously, the inversion of the MV data has lead to more accuracy in the depth resolution.

3-2 Horizontal resolution

The second synthetic model consists of five 1-ohm-m conductors that have dimensions of 15 km*15 km at the depth of 15 km. They are separated by 30 km from each other (Figure 3-a). Theoretical responses of the model for the characteristic period of 1024 s are displayed in Figures 3-b and 3-c. Five zero values of tipper and five maximum values of MV data are obvious. The amplitude of the tipper is significantly decreased in the middle of the profile. Figure 4 shows the models resulted from the inversion of the MV and the tipper data. Although separation of conductors is better detected in the model resulted from the inversion of the tipper data, their conductivities are underestimated, especially for the conductors located in the middle. On the whole, the model based on the inversion of the MV data seems preferable.

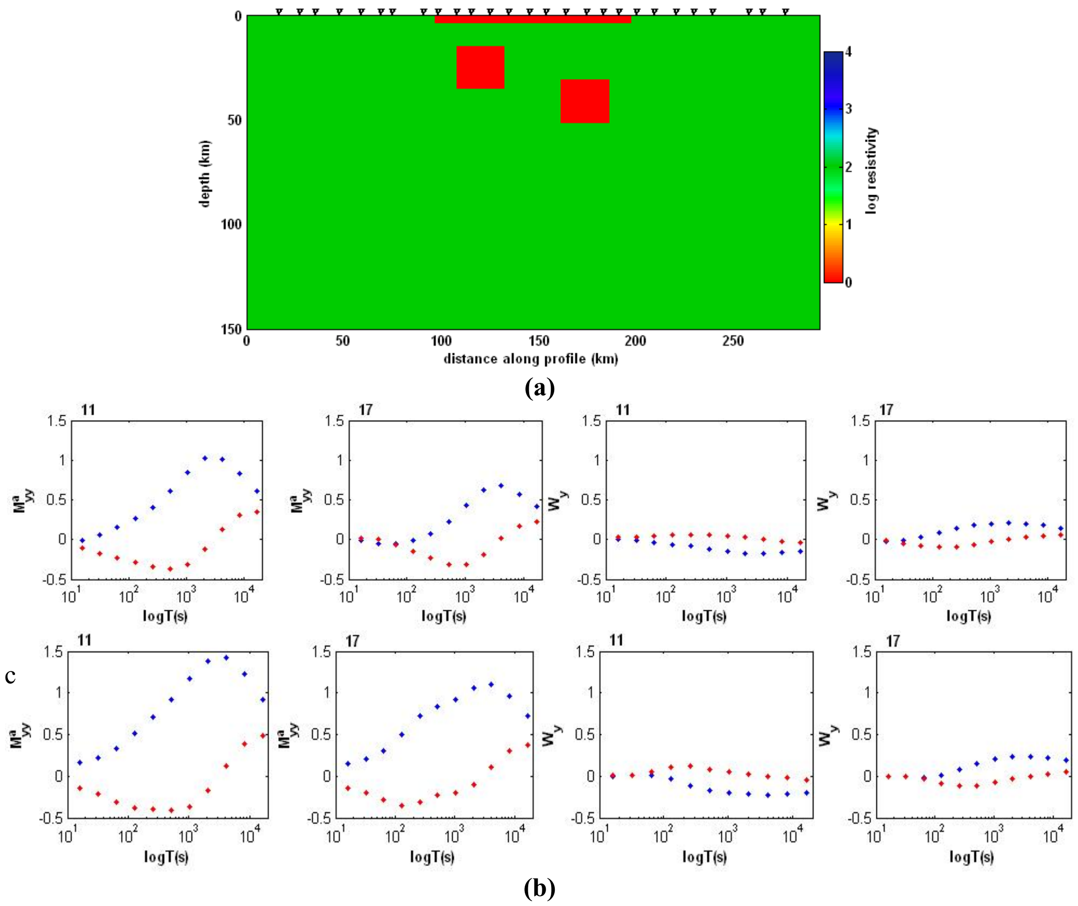
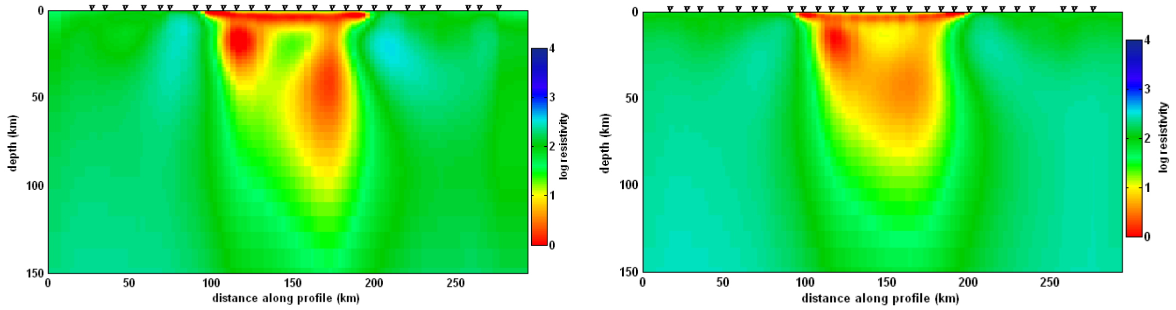
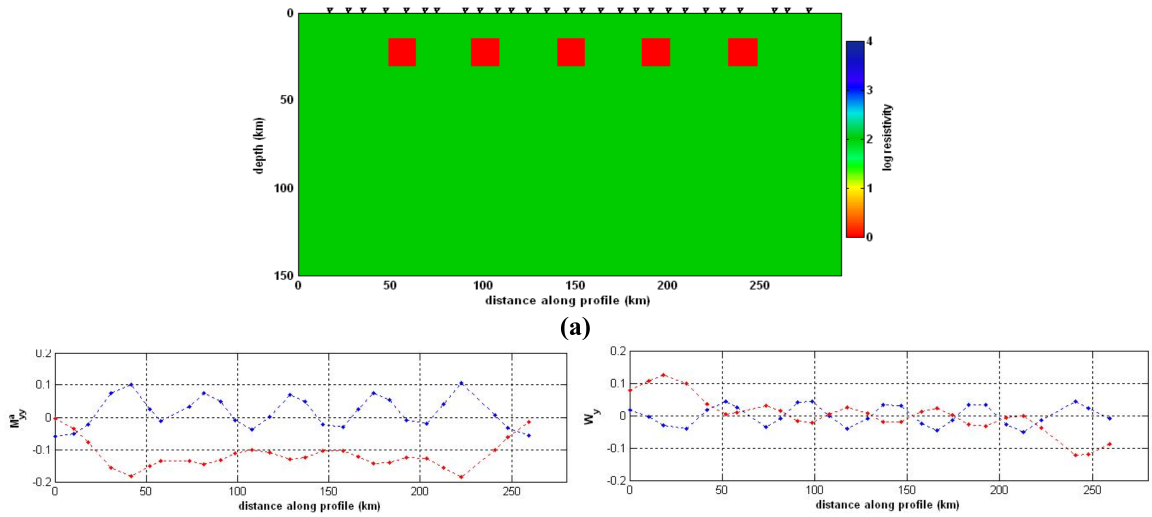


Figure 1. The first synthetic model, including two conductive anomalies beneath an overburden (a), theoretical responses at two example stations (b), and theoretical responses at two example stations for the case without overburden (c), a 2 % Gaussian noise is added.



(a) (b)

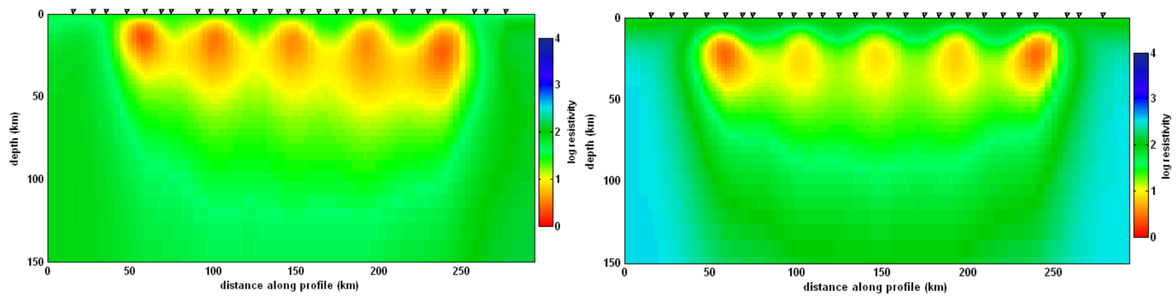
Figure 2. Resistivity model resulted from inversion of the magnetovariational data (a), and tipper (b) corresponding to the synthetic model in Figure 1.



(a)

(b) (c)

Figure 3. The second synthetic model, including five conductive anomalies at the same depth interval inside a homogenous half-space (a), and theoretical responses at the characteristic period of 1024 s. 2 % Gaussian noiseis added (b) and (c).



(a) (b)

Figure 4. Resistivity model resulted from an inversion of the magnetovariational data (a), and tipper (b) corresponding to the synthetic model in Figure 3.

3-3 Sensitivity to the vertical changes of the conductivity

The third synthetic model consists of four layers with resistivities of 100, 1000, 100 and 10 ohm-m from the surface. Inside the first layer, a 1-ohm-m block with dimensions of 10 x 80 km^2 is embedded (Figure 5-a). In Figure 5-b magnetic responses computed for the two stations are displayed. Both data can identify the layered structure. In the absence of lateral changes, magnetic transfer functions vanish. However, when horizontally in homogeneities occur and magnetic responses are non-zero, they contain information about the distribution of conductivity in all directions. The model demonstrates that the MV data and tipper, in contrast to the common expectation, are not completely insensitive to the layered structure. In terms of changes, the MV data are more sensitive.

4 Field example

The data set considered here correspond to a northeastward directed profile passing through the Trans European Suture Zone (TESZ) in northwest of Poland (Brasse et. al., 2006). This zone is the most prominent tectonic boundary in Europe that stretches from the North Sea to the Black Sea. The profile of the data has exact similar configuration as those mentioned for the synthetic data. The period range of the data is slightly different, i.e. 30 - 20000 s for vertical and 100 – 20000 s for horizontal magnetic data. To calculate inter-station magnetic transfer functions, a reference is needed. It cannot be located on a true normal section in real conditions and has been selected near the edge of the profile, located as far as possible from strong anomalies. Real and imaginary parts of the tipper and inter-station horizontal magnetic data are displayed in Figure 6. The models resulting from the inversion of horizontal and vertical magnetic data are shown in Figure 7.

From geological and geophysical studies, it is known that the section over which the reference site is located has large values of resistivity at the lower crustal and upper mantle depths. As inter-station horizontal magnetic data reflect changes of resitivity between observation and reference stations, we do not expect to see the resistor in the model resulting from their inversion; while it is evident in the model resulting from the inversion of the tipper data. In both models, on the other hand, high conductivities have been appeared at the central parts of the profile, consistent with the previous results over the area. It seems that the most important issue, regarding real data set, is to consider the location of the base site in the interpretation of the inter-station horizontal magnetic transfer functions.

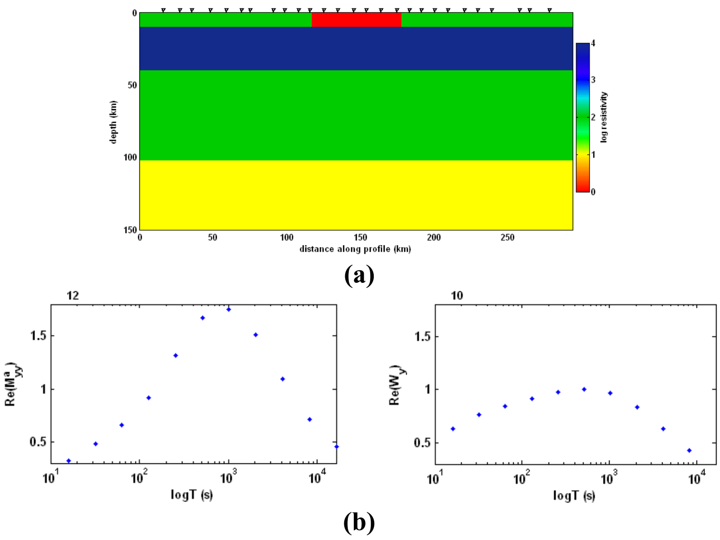


Figure 5. Third synthetic model, including four-layered structure (a), and theoretical responses at two characteristic stations (b).

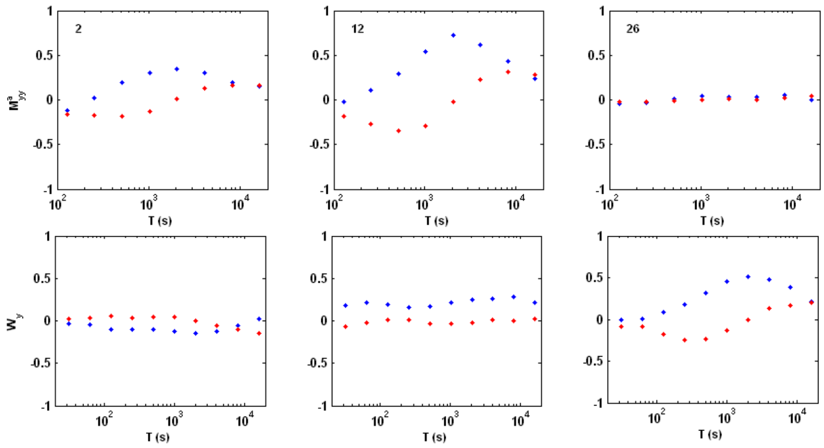


Figure 6. Horizontal and vertical magnetic data from field example for three characteristic sites (blue: real parts; red: imaginary parts).

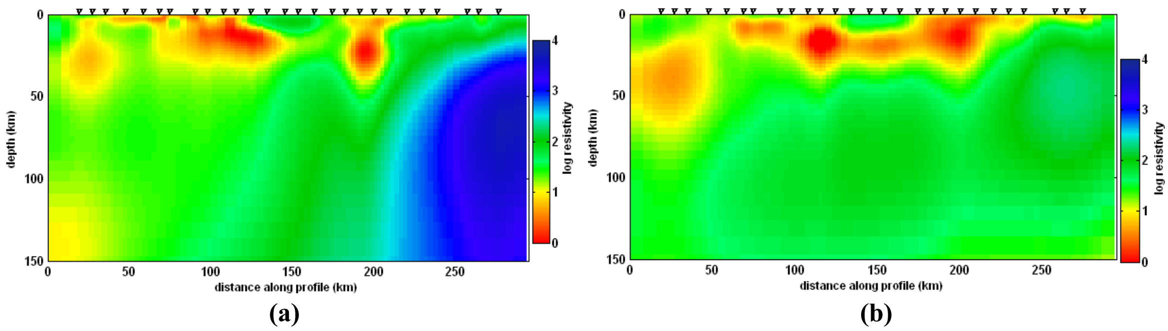


Figure 7. Resistivity model resulted from an inversion of the tipper data (a), and magnetovariational data (b) corresponds to the real data set.

5 Conclusion

Considering the results of the synthetic tests, we can point out some characteristics of the horizontal and vertical magnetic data, with emphasize on relative advantages of models based on the MV data.

In the presence of very conductive overburden, for which the resolution of deep structures is strongly degraded, the difference between two transfer functions has the highest value. As the effects on the data due to conductors are weak, resistivity contrasts are underestimated, especially for the model resulted from the inversion of tipper and for the case of a deep conductive block. While the deep conductor has not been detected and is not distinguishable from the shallow one in the model based on tipper data inversion, in the model resulted from the MV data inversion, the two conductors are completely detected and distinguished from each other. Underestimation of conductivity only occurs for the deep block, which is less significant. Therefore, the MV data modeling improves the depth resolution and yields more reliable information of deep targets, in comparison with the tipper data. However, as a disadvantage, in the inversion model for the MV data, the conductors extend to the greater depths and from this point of view, tipper looks preferable.

In the second synthetic model, including several closely located conductors at similar depth, the two data-components yield more comparable results. Both of them reveal features with poor resolution in lateral boundaries. However, inter-station horizontal magnetic transfer functions seem to have a higher accuracy for imaging conductivities. But higher resolution in lateral boundaries can be obtained through the inversion of the tipper data.

Vertical and inter-station horizontal magnetic responses, in the presence of lateral structures, can also resolve vertical changes of conductivity, as it is observed in the third synthetic model. Although efficiency of the MV data to infer the distribution of resistivity, at least for simple synthetic models considered in this paper, has been demonstrated, their effectual application for real data is not easy. The simultaneous measurements with respect to several references and then selection a unique base for the whole array should be conducted carefully. In addition, inhomogeneities in the location of the base station are reflected in the MV data; therefore selection of a final base on an unanomalous section is also an important procedure. This challenging issue manifests itself through inversion of the real data set.

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