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A telluric method for natural field induced polarization studies

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ABSTRACT

Natural field induced polarization (NFIP) is a branch of low-frequency electromagnetics designed for detection of buried polarizable objects from magnetotelluric (MT) data. The conventional approach to the method deals with normalized MT apparent resistivity. We show that it is more favorable to extract the IP effect from solely electric (telluric) transfer functions instead. For lateral localization of polarizable bodies it is convenient to work with the telluric tensor determinant, which does not depend on the rotation of the receiving electric dipoles.

Applicability of the new method was verified in the course of a large-scale field research. The field work was conducted in a well-explored area in East Kazakhstan known for the presence of various IP sources such as graphite, magnetite, and sulfide mineralization. A new multichannel processing approach allowed the determination of the telluric tensor components with very good accuracy. This holds out a hope that in some cases NFIP data may be used not only for detection of polarizable objects, but also for a rough estimation of their spectral IP characteristics.

1. Introduction

The idea of applying natural EM field for the detection of buried polarizable objects first appeared in the second half of the 20th century, when the magnetotelluric (MT) method was undergoing a period of rapid development. Since MT method deals with significant depths without any cumbersome transmitters, there was always great interest in its application for the exploration of deep IP targets. Pioneer papers on the subject were published by Shaydurov (1967), Ware (1974), Wu and Wang (1978), and others. From later theoretical investigations, the most known and notable is that of Gasperikova and Morrison (2001).

First practical attempts to extract the IP response from field MT data were performed by Keeva Vozoff in late 1960s (Seigel et al., 2007), but the resolution of the measuring equipment at that time turned out to be insufficient for the task. Over time, Murali et al. (1980), Yang et al. (2000, 2008), and Gasperikova et al. (2005) reported limited success in attempting to do the same, thus giving the official birth to the method of natural field induced polarization (NFIP).

IP concept is based on the fact that intrinsic resistivity $\rho(\omega)$ of a polarizable body decreases with frequency ω. In conventional controlled-source IP, where the investigation depth depends only on electrode arrangement, for any particular survey there always exists a threshold frequency, below which (within the so-called *DC limit*) the secondary induction currents are negligible and all observable changes of complex-valued apparent resistivity are indicative of IP effects.

In magnetotellurics, the depth of investigation depends on frequency, therefore even in a simple layered 1D medium and at arbitrarily low frequencies an IP response may always be confused with a mere *EM sounding effect* caused by penetration of magnetotelluric field deeper into underlying geoelectric strata. A simple and reliable solution of the problem is to normalize the MT response under study by that at a remote reference site, thus excluding the influence of the regional 1D background from the measured data (Gasperikova and Morrison, 2001; Yang et al., 2008). As a result, *NFIP anomalies are always relative* and their zero value is freely selectable, which is important to keep in mind for correct interpretation of measured data.

Feasibility of the existing NFIP technique is proven only for 2D objects (Gasperikova et al., 2005; Yang et al., 2008). Below we show that this limitation may be overcome by making use of solely electrical (telluric) transfer functions, thus notably expanding potential capabilities of the method.

Another important constraining factor of NFIP is data accuracy. We developed a new processing algorithm, which employs all measured EM components at both local and remote sites, thus increasing the determination accuracy of telluric tensor by several times compared to the conventional processing approach.

2. Theory

2.1. MT transfer functions

In this subsection we briefly describe some definitions and properties of several magnetotelluric transfer functions relevant to NFIP method. The following equations represent the fundamentals of MT theory

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and could be found at Berdichevsky and Dmitriev (2008), Chave and Jones (2012), or any other monograph on the subject.

The topmost MT transfer function is the complex-valued *impedance tensor* $\hat{\mathbf{Z}}$, which relates the electric $\boldsymbol{E}=(E_x,E_y)$ and magnetic $\boldsymbol{H}=(H_x,H_y)$ components of horizontal EM field at the ground surface as follows

$$\begin{bmatrix} E_x(\omega) \\ E_y(\omega) \end{bmatrix} = \begin{bmatrix} Z_{xx}(\omega) & Z_{xy}(\omega) \\ Z_{yx}(\omega) & Z_{yy}(\omega) \end{bmatrix} \begin{bmatrix} H_x(\omega) \\ H_y(\omega) \end{bmatrix}. \tag{1}$$

The impedance tensor is the only MT transfer function that could be formally translated into apparent resistivity ρ_a. The latter is determined by all $\hat{\mathbf{Z}}$ components and generally represents a tensor quantity; thus, in complex geological situations it is often convenient to use its effective value, which could be defined as follows

$$\rho_{eff}(\omega) = \frac{Z^2_{eff}(\omega)}{-i\omega\mu_0} = \frac{detZ(\omega)}{-i\omega\mu_0}, \tag{2}$$

where $i=\sqrt{-1}$, μ_0 is the vacuum permeability, $Z_{eff}(\omega) =^{def} \sqrt{Z_{xx}(\omega)Z_{yy}(\omega)-Z_{xy}(\omega)Z_{yx}(\omega)}$ denotes the effective impedance (Berdichevsky and Dmitriev, 2008), and $detZ(\omega) =^{def} \det[\hat{\mathbf{Z}}(\omega)]$ stands for the impedance tensor determinant.

If the EM field is also measured at a remote reference site, then its electric $\boldsymbol{E^{rem}}=(E^{rem}_x,E^{rem}_y)$ and magnetic $\boldsymbol{H^{rem}}=(H^{rem}_x,H^{rem}_y)$ components are related with those at a survey site as follows

$$\begin{bmatrix} E_x(\omega) \\ E_y(\omega) \end{bmatrix} = \begin{bmatrix} T_{xx}(\omega) & T_{xy}(\omega) \\ T_{yx}(\omega) & T_{yy}(\omega) \end{bmatrix} \begin{bmatrix} E^{rem}_x(\omega) \\ E^{rem}_y(\omega) \end{bmatrix}, \tag{3a}$$

$$\begin{bmatrix} H_x(\omega) \\ H_y(\omega) \end{bmatrix} = \begin{bmatrix} M_{xx}(\omega) & M_{xy}(\omega) \\ M_{yx}(\omega) & M_{yy}(\omega) \end{bmatrix} \begin{bmatrix} H^{rem}_x(\omega) \\ H^{rem}_y(\omega) \end{bmatrix}, \tag{3b}$$

where $\hat{\mathbf{T}}$ and $\hat{\mathbf{M}}$ are called *telluric tensor* and *horizontal magnetic tensor*, respectively.

In a 2D medium the EM field is decomposed into two independent modes: in the *TE mode* the electric field is aligned along the strike, whilst in the *TM mode* — perpendicular to it. Let the x axis be perpendicular to strike. Then the introduced MT transfer functions are simplified to

$$\hat{\mathbf{Z}}_{2D}(\omega) = \begin{bmatrix} 0 & Z_{xy}(\omega) \\ Z_{yx}(\omega) & 0 \end{bmatrix}, \tag{4a}$$

$$\hat{\mathbf{T}}_{2D}(\omega) = \begin{bmatrix} T_{xx}(\omega) & 0 \\ 0 & T_{yy}(\omega) \end{bmatrix}, \tag{4b}$$

$$\hat{\mathbf{M}}_{2D}(\omega) = \begin{bmatrix} M_{xx}(\omega) & 0 \\ 0 & 1 \end{bmatrix}. \tag{4c}$$

Note that $M_{yy}(\omega)\equiv 1$, thus making the 2D TM mode unique in that it is *the only multidimensional MT case with magnetic component H_y being constant along any survey line.* As a result, for the calculation of the normalized TM-mode resistivity $\tilde{\rho}_{TM}(\omega)$ it is sufficient to measure components E_x and E^{rem}_x of magnetotelluric signal (Gasperikova and Morrison, 2001). At the same time, the TM-polarized 2D geoelectrical environment is the only case reported to be eligible for NFIP method so far (Gasperikova et al., 2005; Yang et al., 2008): this coincidence naturally allows suggesting that application of solely electrical MT transfer functions in a general 3D case may yield better results.

2.2. Telluric approach to NFIP

According to Eq. (2), the normalized effective resistivity $\tilde{\rho}_{eff}$ may be represented as follows

$$\tilde{\rho}_{eff}(\omega) = \frac{\rho_{eff}(\omega)}{\rho^{rem}_{eff}(\omega)} = \frac{detZ(\omega)}{detZ^{rem}(\omega)}. \tag{5}$$

Using the properties of square matrix determinant it could be shown (Appendix A) that

$$detZ(\omega)detM(\omega) = detT(\omega)\, detZ^{rem}(\omega), \tag{6}$$

which yields the following expression for $\tilde{\rho}_{eff}(\omega)$

$$\tilde{\rho}_{eff}(\omega) = \frac{detT(\omega)}{detM(\omega)}. \tag{7}$$

Thus, in an arbitrary 3D case, the normalized effective resistivity could always be decomposed into two independent complex-value components — electric *detT* and magnetic *detM*. Each of these components over a non-polarizable medium tends to a real constant value at $\omega\rightarrow 0$, and hence may be used as a standalone NFIP parameter, on the same basis as $\tilde{\rho}_{eff}$. We will further consider the effective values of the abovementioned tensors, namely $T_{eff}=\sqrt{detT}$ and $M_{eff}=\sqrt{detM}$, which carry the same information as the corresponding tensor determinants, but are more convenient for application in practice (e.g. it could be shown that T_{eff} IP anomalies are similar to those obtained by the application of a conventional rectangular IP/resistivity array with sufficiently large electrode spacing).

NFIP measurements are dramatically exposed to EM distortions caused by secondary induction currents in conductive media (Luo et al., 2003). As in the case of conventional IP technique, in order to make such EM effects negligible one should only use the frequencies low enough to be considered as lying within the *DC limit*. In the context of magnetotellurics, this means that the effective skin depth must exceed by far the depth of burial of all local geoelectrical objects, thus technically turning them into subsurface inhomogeneities (from the standpoint of conventional MT sounding). Hence, for being able to reliably detect a polarizable body, the chosen MT transfer function must be sensitive to the inherent resistivity of near-surface objects. From the numerous investigations on that subject (Berdichevsky and Dmitriev, 1976; Bahr, 1988; Groom and Bailey, 1991; etc.) we know that the strong influence of subsurface inhomogeneities on the apparent resistivity curves (the so-called *static shift effect*) lies entirely in the electric field and leaves the horizontal magnetic components almost unaffected. As a result, we may conclude that T_{eff} is much more sensitive to IP effects than M_{eff}. From this clearly follows that the *magnetic part of $\tilde{\rho}_{eff}$ at low frequencies contains virtually no IP information and may only act as a source of additional noise for NFIP method.*

3. Modeling

This section is aimed to demonstrate the advantages and limitations of the proposed telluric NFIP technique on model examples. All numerical calculations were made with the help of 3D finite-element code developed by Mackie (2002), which does not allow working with frequency-dependent resistivities. Since none of the bodies in the present model study are polarizable, all the calculated phase curves represent EM noise for NFIP method. If the phase value is less than 0.1° (~2 mrad) in modulus, it is considered to be *negligibly small* and is not plotted on the figures below to mark out the “free of EM coupling” period range (DC limit) suitable for extracting IP information.

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