Telluric method of natural field induced polarization

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SUMMARY

Conventional induced polarization (IP) methods are very useful in shallow exploration, but may become a considerable challenge (especially in difficult areas) when the depth of interest exceeds 50 - 100 meters, making it necessary to work with significant dipole separation and cumbersome power source. Therefore there was always a great interest in extracting information of IP from magnetotellurics (MT) data, now giving rise to a new branch of Low Frequency EM called Natural Field Induced Polarization (NFIP). The major challenge of NFIP is how to distinguish the weak IP anomaly from the strong EM noise caused by inductive effects in the medium. It is shown below, that for getting best results one should use electric (telluric) components of the MT field, namely the ratio of the electric field at a survey point to the reference electric field at some remote site (i.e. components of so-called *telluric tensor*). Over a non-polarizable medium under certain conditions and at a sufficiently low frequency phase of the ratio is directly proportional to frequency, and magnitude is almost frequency-independent. Application of the formulas that take into account these features of telluric field allows to significantly attenuate inductive noise and to extract the IP response from both phase and absolute value of telluric tensor (TT) components.

The proposed approach was tested on a number of 2D and 3D models; numerical experiments showed reliable results. At present we are working on development of the theoretical basis and application area of the method, adjustment of the operational frequency band etc. It is also planned to carry out a series of experiments to apply the approach to real field data.

Keywords: induced polarization, natural field, natural source, magnetotellurics, modeling, Cole-Cole

INTRODUCTION

If a media is polarizable, in the frequency domain IP effect appears as frequency dispersion of resistivity . The best-known mathematical model of the phenomena is known as Cole-Cole representation:

$$\rho(\omega) = \rho_0 \left\{1 - \eta \left[1 - \frac{1}{1 + (j\omega\tau)^{C}}\right]\right\} \quad (1)$$

with ρ_0 denoting the low-frequency resistivity asymptote, η - the chargeability, τ - the time constant and C - the dimensionless constant, which controls the spectral width of the effect. $\rho(\omega)$ is a complex-valued function, its amplitude and phase curves (schematically represented by Figure 1) show that IP effect reduces apparent resistivity with frequency and causes negative phase shift of electric signal. Both of these two features are widely used in conventional IP surveys – phase shift is considered as a direct indication of IP effect, and in the amplitude domain it is suitable to use so-called Percent Frequency Effect (PFE) defined as follows (van Voorhis et al., 1973):

$$PFE(\omega_h, \omega_l) = \left[1 - \frac{\rho_a(\omega_h)}{\rho_a(\omega_l)}\right] \cdot 100\% \quad (2)$$

where $\rho_a(\omega_l)$ and $\rho_a(\omega_h)$ stand for apparent resistivity at higher and lower frequencies respectively.

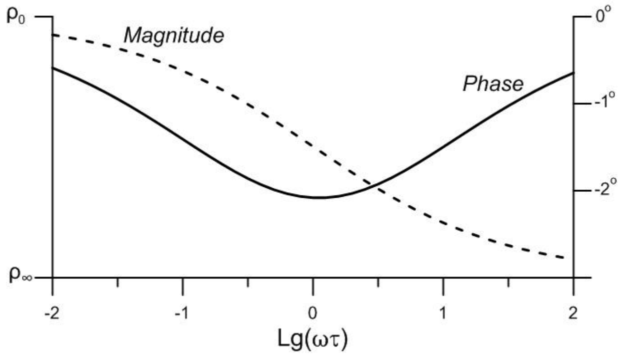

Figure 1. Amplitude and phase of Cole-Cole function.

Ware (1974) first tried to apply conventional IP approach to MT data by formal substitution of Cagniard apparent resistivity into equation (2). He found that for a finite 2D body in TM mode (electric field is perpendicular to strike) there is a frequency ω_c, below which inductive effects are negligible. In this low frequency band (also called the *dc limit*) any anomaly calculated in the equation (2) would indicate the IP effect. However, this approach is not applicable even to a horizontally-layered medium, where the change of apparent resistivity with frequency is primarily due to sounding effect rather than IP. Thereby several researchers (Gasperikova et al., 2005; Yang et al., 2008) proposed to use Relative PFE (RPFE), which most elegant version is a simple subtraction from the calculated PFE of appropriate background value, obtained at a remote site (over the 1D medium):

$$RPFE^j = PFE^j - PFE^{rem} \quad (3)$$

for every j[th] survey point.

First attempts to use the phase shift of MT signal for detecting IP were carried out soon thereafter. Gasperikova and Morrison (2001) showed that 2D polarizable body in TM mode can be detected by appearance of imaginary part (i.e. phase shift) in survey-to-reference ratio of the electric field. They also pointed out at the significant influence of inductive effect on this technique.

Both of two described approaches (RPFE and phase) were quite successfully tested on real data – they gave observable anomalies over preliminary explored strongly polarizable bodies (Gasperikova et al., 2005; Yang et al., 2008). Nevertheless NFIP never gained high popularity because of a number of unresolved problems – narrow field of application (2D bodies in TM mode), significant influence of inductive distortion (especially in phase method), necessity to obtain data of superior quality etc.

THEORETICAL BACKGROUND

EM field over the heterogeneous earth is composed of normal and anomalous parts, related to 1D medium and the field of secondary sources (associated with inhomogeneity), respectively. Since the regular field is identical for all survey points, the frequency response of MT transfer function mainly depends on the field of secondary sources and its distortion related to inductive effects in medium. Most of elementary sources of EM field have the following property (Svetov, 2008): in the near-field zone the imaginary part of electric component of their field is directly proportional to frequency, whilst the real part is nonzero and frequency-independent. It means that at a sufficiently low frequency (and a close distance – near-field zone requirement) the amplitude of electric field of secondary sources is constant, while its phase shift is a linear function of frequency and therefore can be considered analytically. Furthermore, Kulikov and Shemyakin (1978) pointed out that IP effect is more pronounsed in electric rather than in magnetic field. All of this allows us to state that the IP response should be extracted from pure electrical transfer functions, i.e. from the components of telluric tensor $\hat{T}$, which links the electric field $\tilde{\mathbf{E}}^j$ at j[th] survey point with electric field $\tilde{\mathbf{E}}^{rem}$ at a remote site:

$$\tilde{\mathbf{E}}^j(\omega) = \hat{T}(\omega) * \tilde{\mathbf{E}}^{rem}(\omega) \quad (4)$$

or

$$\begin{bmatrix} \tilde{E}_x^j(\omega) \\ \tilde{E}_y^j(\omega) \end{bmatrix} = \begin{bmatrix} \tilde{T}_{xx}(\omega) & \tilde{T}_{xy}(\omega) \\ \tilde{T}_{yx}(\omega) & \tilde{T}_{yy}(\omega) \end{bmatrix} \begin{bmatrix} \tilde{E}_x^{rem}(\omega) \\ \tilde{E}_y^{rem}(\omega) \end{bmatrix} \quad (5)$$

where $\tilde{E}_x$ and $\tilde{E}_y$ stand for projections of complex-valued vector $\tilde{\mathbf{E}}$ of electric field on coordinate axes. $\tilde{T}_{xx}$ and $\tilde{T}_{yy}$ (primary components of $\hat{T}$) contain the principal information on the resistivity and polarizability of the medium; $\tilde{T}_{xy}$ and $\tilde{T}_{yx}$ (secondary components of $\hat{T}$) are much smaller than primary ones and contain the information on inhomogeneity of the cross-section. Thus for detecting the IP effect we will use $\tilde{T}_{xx}$ and $\tilde{T}_{yy}$, which can be conveniently expressed in exponential form (with $i = \sqrt{-1}$):

$$\begin{cases} \tilde{T}_{xx} = T_{xx} e^{i\varphi_x} \\ \tilde{T}_{yy} = T_{yy} e^{i\varphi_y} \end{cases} \quad (6)$$

AMPLITUDE METHOD

Let us define the Telluric Percent Frequency Effect (TPFE) through the primary components of $\hat{T}$ in such a way that it will coincide with RPFE in 2D medium. From formulae (3) and (2) we have:

$$RPFE^j = \left[\frac{\rho_a^{rem}(\omega_h)}{\rho_a^{rem}(\omega_l)} - \frac{\rho_a^j(\omega_h)}{\rho_a^j(\omega_l)}\right] \cdot 100\% =$$

$$= \frac{\rho_a^{rem}(\omega_h)}{\rho_a^{rem}(\omega_l)} \cdot \left[1 - \frac{\rho_a^j(\omega_h)}{\rho_a^j(\omega_l)} \cdot \frac{\rho_a^{rem}(\omega_l)}{\rho_a^{rem}(\omega_h)}\right] \cdot 100\% \quad (7)$$

Let the x axis be perpendicular to strike. Then for TM mode we have:

$$\rho_a(\omega) = \rho_x(\omega) = \frac{|Z_\perp|^2}{\omega\mu} = \frac{(E_x/H_y)^2}{\omega\mu} \quad (8)$$

Considering the fact that in TM mode magnetic field H_y is constant along the profile, the ratio in square brackets from (6) can be rewritten as follows:

$$\frac{\rho_a^j(\omega_h)}{\rho_a^j(\omega_l)} \cdot \frac{\rho_a^{rem}(\omega_l)}{\rho_a^{rem}(\omega_h)} = \left(\frac{E_x^j(\omega_h)}{E_x^j(\omega_l)}\right)^2 \cdot \left(\frac{E_x^{rem}(\omega_l)}{E_x^{rem}(\omega_h)}\right)^2 =$$

$$= \left(\frac{T_{xx}^j(\omega_h)}{T_{xx}^j(\omega_l)}\right)^2 \quad (9)$$

Last equality in (9) holds since in 2D medium $T_{xy}^j(\omega) = T_{yx}^j(\omega) = 0$ and hence $E_x^j(\omega) = T_{xx}^j(\omega) \cdot E_x^{rem}(\omega)$ for every j[th] point of the profile. By substitution of (9) to (7) we may formulate a final expression for TPFE:

$$TPFE_x^j = \frac{\rho_x^{rem}(\omega_h)}{\rho_x^{rem}(\omega_l)} \cdot \left[1 - \left(\frac{T_{xx}^j(\omega_h)}{T_{xx}^j(\omega_l)}\right)^2\right] \cdot 100\% \quad (10)$$

Thus defined $TPFE$ can be applied in 3D medium - to obtain an expression for $TPFE_y$ one should simply use indexes y instead of x in (10) - while in 2D situation $TPFE \equiv RPFE$ by definition.

PHASE METHOD

As shown above, at a sufficiently low frequency the induction phase shift φ_{ind} of electric field is a linear function of frequency, while the IP phase φ_{ip} depends weakly on the frequency and in a narrow frequency band this dependence can be neglected. In this case, the phase φ of telluric tensor can be written as follows:

$$\varphi(\omega) = \varphi_{ind}(\omega) + \varphi_{ip}(\omega) = \chi\omega + \varphi_{ip} \quad (11)$$

By measuring the phase value at two different frequencies we get the following system of linear equations:

$$\begin{cases} \varphi(\omega_1) = \chi\omega_1 + \varphi_{ip} \\ \varphi(\omega_2) = \chi\omega_2 + \varphi_{ip} \end{cases} \quad (12)$$

Solution of the system (12) with respect to unknown variable φ_{ip} defines so-called Differential-Phase Parameter (DPP) $\Delta\varphi$, which can be used for estimating the IP phase:

$$\Delta\varphi(\omega_1, \omega_2) = \frac{\varphi(\omega_1) \cdot \omega_2 - \varphi(\omega_2) \cdot \omega_1}{\omega_2 - \omega_1} \quad (13)$$

The described approach (applied to conventional IP exploration) was brought forward by Kulikov and Shemyakin (1978). It is obvious that if IP phase is indeed frequency-independent, then $\Delta\varphi = \varphi_{ip}$. In practice, this condition is not always satisfied and the IP phase value obtained from (13) sometimes happens to be slightly underestimated. Nevertheless, $\Delta\varphi$ perfectly reduces inductive noise and is a good estimation of φ_{ip}; therefore it has been widely used in Russian conventional IP surveys for many years.

MODEL STUDY

To compare the new approach with the existing methods of NFIP, several experiments were conducted on 2D and 3D models. As mentioned above, the fact that phase and amplitude methods provide detectable anomalies over polarizable bodies was verified in practice. Thus, the main question is that of inductive noise and ways of its suppression, and therefore the modeling was mainly dedicated to this subject. For this purpose we used the NWMT2D (courtesy of Nord-West Ltd.) and MT3FWD (Mackie, 2002) software.

2D

In the absence of IP effects, the negative phase anomalies of telluric tensor are confined to conductive bodies, while the positive ones indicate the bodies with high resistivity. Since IP phase anomalies are negative they can be mixed up with inductive anomaly over conductive body. To demonstrate this effect the following model was constructed (Figure 2):

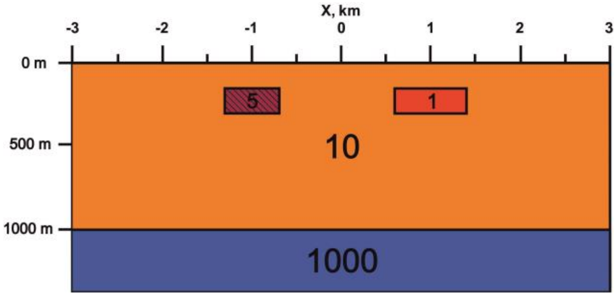

Figure 2. 2D model (polarized body is shaded).

in nonpolarizable sedimentary rocks ($\rho = 10\ Ohm \cdot m$) there are two conductive bodies. One of them is polarizable ($\rho = 5\ Ohm \cdot m$; $\eta = 10\%$; $\tau = 3c$; $C = 0.5$) and another one is a few more conductive ($\rho = 1\ Ohm \cdot m$). To meet the conditions of near-field zone it is usually sufficient to use frequencies below $0.05\ Hz$, thus the model was calculated for the frequency of $0.02\ Hz$. Model parameters have been chosen so that the phase anomalies over the polarized body (Figure 3a, left) and the other one (Figure 3a, right) are virtually identical.

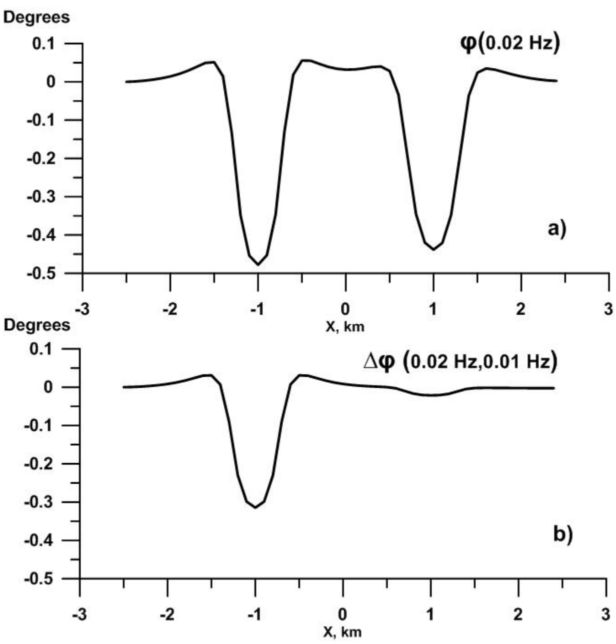

Figure 3. Phase (a) and DPP (b) curves.

The direct interpretation of these anomalies will obviously lead to an error, while the application of DPP, calculated by (13) for two frequencies (e.g. $0.02\ Hz$ and

0.01 Hz) reduces inductive part of the anomalies and so allows us to confidently distinguish them (Figure 3b). This model helped us to compare two phase methods. As far as in 2D medium TPFE ≡ RPFE, the comparison of these two parameters is considered further.

3D

To demonstrate the difference between mentioned methods in 3D case, the high contrast model of sedimentary basin with a small conductive body and significant basement uplift was constructed (Figure 4).

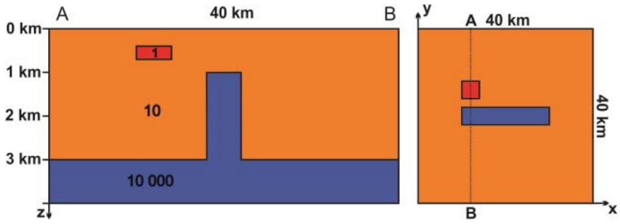

Figure 4. 3D model: cross-section and plan view.

The model does not contain any polarizable objects, so every NFIP anomalies over it are caused only by inductive effects. From the Figure 5a it is clear that the phase anomaly φ is high enough even at the lowest frequency (0.012 Hz) from the represented band – about 1° along the x axis and 2° along the y axis. In the same time, the DPP value $\Delta\varphi$ does not exceed 0.2° even at the higher frequencies at both directions (i.e. inductive noise is reduced by an order of magnitude).

The Figure 5b shows the comparison between the amplitude methods of NFIP. It could be seen that at higher frequencies the anomalies of both parameters are quite similar, but at low frequencies TPFE decreases rapidly (to less than 0.5%), while the behavior of RPFE is more complex and its anomaly does not fall below 1%, which is likely caused by increasing influence of magnetic component of EM field at lower frequencies.

CONCLUSIONS

Proposed methods significantly expand the application area of NFIP – from 2D bodies (and only in TM mode) to 3D bodies in layered earth for any direction of measurement. Furthermore the model study clearly shows that the new formulae can protect from inductive noise far better than the previously used ones, including the 2D case for the phase technique. We are currently working on obtaining MT data of sufficiently high quality and on applying the new methods to real data.

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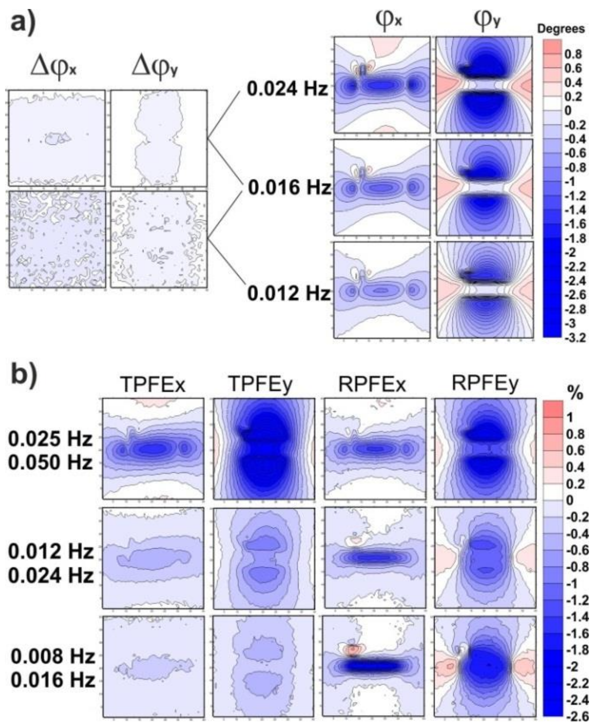

Figure 5. Phase (a) and amplitude (b) maps**.**

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