Available online at www.sciencedirect.com

SciVerse ScienceDirect

Russian Geology and Geophysics 53 (2012) 108–115

RUSSIAN GEOLOGY AND GEOPHYSICS

www.elsevier.com/locate/rgg

Medium and field inhomogeneity: zone of influence during magnetotelluric sounding

V.V. Plotkin *

[a] *A.A. Trofimuk Institute of Petroleum Geology and Geophysics, Siberian Branch of the Russian Academy of Sciences, pr. Akademika Koptyuga 3, Novosibirsk, 630090, Russia*

Received 31 March 2010; accepted 1 March 2011

Abstract

The study is devoted to the possibilities of MTS in the case of arbitrary medium and electromagnetic-field inhomogeneity. It has been shown that the local tensor impedance and admittance ratios between the field components are usually differential. Useful information about the study region, with complex behavior of sounding curves, can be obtained by unconventional processing techniques, with the help of nonlocal medium response functions (component matching). Experiments can be considerably more cost-effective if we divide the study area into several small zones of synchronous observations and perform independent experiments in each of them at different time.

Keywords: magnetotelluric sounding; impedance; admittance; zone of synchronous observations; nonlocal response functions; lateral inhomogeneity; conductivity

Introduction

Researchers have long been interested in methods of correction for distortions in magnetotelluric curves caused by the inhomogeneity of the sounding medium. A good overview of field distortions caused by near-surface inhomogeneities in the medium and the influence of the surface relief as well as ways of their elimination is given in (Jiracek, 1990). Distortions are divided into two types: induction and galvanic. The former are due to the redistribution of current, and the latter are due to the appearance of additional electric charges in the inhomogeneous medium. In (Singer, 1992), size estimates of the region (normalization radius) are given within which the influence of distant inhomegeneities on distortions of magnetotelluric curves cannot be neglected.

The primary field is usually described as a vertically incident wave with different polarization relative to long 2D inhomogeneities; this suggests a TE or TM mode of excitation. The situation becomes more complex in the case of a 3D environment and a more complex structure of the natural electromagnetic field (Guglielmi, 2009; Semenov, 2009). However, there are also two modes of the field in this case, but TE and TM are interrelated (Plotkin et al., 2008). Three-dimensional effects in the Born approximation were studied in (Torres-Verdín and Bostick, 1992a), and a way of correction for them with the help of spatial-surface electric-field filtering (electromagnetic array profiling) was described in (Torres-Verdín and Bostick, 1992b). The present paper analyzes another possible approach to solving this problem, based on component matching (Plotkin, 2005).

Differential impedance and admittance ratios

Local distortions in the magnetotelluric field are usually studied through the behavior of amplitude and phase sounding curves, obtained by an impedance tensor. The use of the latter is based on the Tikhonov–Cagniard model for a horizontally layered medium excited by a vertically incident plane wave. In general, the components of the impedance tensor depend on the degree of field and environment inhomogeneity. This is evident if we use differential ratios similar to impedance ones. Indeed, excluding the vertical component of the electric field from the Maxwell equations (the OX and OY axes lie on the horizontal plane, and the OZ axis is vertical)

$$-i\omega\mu_0 H_x = \frac{\partial E_z}{\partial y} - \frac{\partial E_y}{\partial z}, \quad -i\omega\mu_0 H_y = \frac{\partial E_x}{\partial z} - \frac{\partial E_z}{\partial x},$$

$$\sigma E_z = \frac{\partial H_y}{\partial x} - \frac{\partial H_x}{\partial y}, \qquad (1)$$

* Corresponding author.
E-mail address: plotkinvv@ipgg.nsc.ru (V.V. Plotkin)

1068-7971/$ - see front matter © 2012, V.S. Sobolev IGM, Siberian Branch of the RAS. Published by Elsevier B.V. All rights reserved.
doi:10.1016/j.rgg.2011.12.008

we obtain

$$\frac{\partial}{\partial z}E_x = -\frac{\partial}{\partial x}\frac{1}{\sigma}\frac{\partial}{\partial y}H_x - \left(i\omega\mu_0 - \frac{\partial}{\partial x}\frac{1}{\sigma}\frac{\partial}{\partial x}\right)H_y\,,$$
$$\frac{\partial}{\partial z}E_y = \left(i\omega\mu_0 - \frac{\partial}{\partial y}\frac{1}{\sigma}\frac{\partial}{\partial y}\right)H_x + \frac{\partial}{\partial y}\frac{1}{\sigma}\frac{\partial}{\partial x}H_y\,. \qquad (2)$$

For a plane wave vertically incident on a horizontally layered medium, these differential ratios turn into common tensor impedance ones. In the case of a horizontally layered medium, they will remain the same for a field with components showing linear lateral variation in the vicinity of the sounding site. In general, the field components included in (2) have to be solutions of the Maxwell equations depending on the conductivity distribution in the entire studied volume. We are hardly warranted in believing that ratios (2) always yield a standard impedance tensor. Even if it is so, the above impedance differential ratios (2) show clearly that the impedance tensor components can depend considerably on the degree and character of environment and field inhomogeneity.

In the case of an anisotropic medium, these ratios become more complex:

$$\begin{pmatrix} \frac{\partial}{\partial z} + \frac{\partial}{\partial x}\frac{\sigma_{zx}}{\sigma_{zz}} & \frac{\partial}{\partial x}\frac{\sigma_{zy}}{\sigma_{zz}} \\ \frac{\partial}{\partial y}\frac{\sigma_{zx}}{\sigma_{zz}} & \frac{\partial}{\partial z} + \frac{\partial}{\partial y}\frac{\sigma_{zy}}{\sigma_{zz}} \end{pmatrix}\begin{pmatrix} E_x \\ E_y \end{pmatrix} =$$
$$\begin{pmatrix} -\frac{\partial}{\partial x}\frac{1}{\sigma_{zz}}\frac{\partial}{\partial y} & -\left(i\omega\mu_0 - \frac{\partial}{\partial x}\frac{1}{\sigma_{zz}}\frac{\partial}{\partial x}\right) \\ i\omega\mu_0 - \frac{\partial}{\partial y}\frac{1}{\sigma_{zz}}\frac{\partial}{\partial y} & \frac{\partial}{\partial y}\frac{1}{\sigma_{zz}}\frac{\partial}{\partial x} \end{pmatrix}\begin{pmatrix} H_x \\ H_y \end{pmatrix}. \qquad (3)$$

The ratios for tangential components are interrelated. Note that the above impedance differential ratios are true of an arbitrary inhomogeneous field in a 3D inhomogeneous anisotropic medium.

Since we have used only three Maxwell equations out of the whole set, we can, in a similar way, exclude the vertical component of the magnetic field from the remaining equations

$$\sigma E_x = \frac{\partial H_z}{\partial y} - \frac{\partial H_y}{\partial z},\quad \sigma E_y = \frac{\partial H_x}{\partial z} - \frac{\partial H_z}{\partial x}\,,$$
$$-i\omega\mu_0 H_z = \frac{\partial E_y}{\partial x} - \frac{\partial E_x}{\partial y}\,, \qquad (4)$$

and obtain corresponding admittance differential ratios, which are also suitable in the case of a arbitrary inhomogeneous medium and an arbitrary inhomogeneous field:

$$\frac{\partial}{\partial z}H_x = \frac{\partial}{\partial x}\frac{1}{i\omega\mu_0}\frac{\partial}{\partial y}E_x + \left(\sigma - \frac{\partial}{\partial x}\frac{1}{i\omega\mu_0}\frac{\partial}{\partial x}\right)E_y\,,$$
$$\frac{\partial}{\partial z}H_y = -\left(\sigma - \frac{\partial}{\partial y}\frac{1}{i\omega\mu_0}\frac{\partial}{\partial y}\right)E_x - \frac{\partial}{\partial y}\frac{1}{i\omega\mu_0}\frac{\partial}{\partial x}E_y\,. \qquad (5)$$

Importantly, the impedances and admittances in the above formulae are also determined by the vertical derivatives of the tangential components of the electric and magnetic fields. This is especially important for the day surface, at the boundary with the nonconducting atmosphere. Here, an additional condition should be met: the vertical current j_z should be zero. Under this condition, the above differential impedance ratios (2) for an arbitrary inhomogeneous field and any medium look like common impedance ratios for a wave vertically incident on a horizontally layered medium. However, the vertical derivatives of the tangential components of the electric field, as a rule, will not coincide with the corresponding derivatives for a wave vertically incident on a horizontally layered medium. Also, the form of the admittance differential ratios for the day surface does not at all depend on the condition $j_z = 0$. It is also unclear whether the admittance and impedance tensors will be opposites of one another in the general case of an inhomogeneous medium or field.

Component matching: a numerical experiment

Since the tensor components of impedance, admittance, and other response functions depend not only on local conductivity but also on the degree of environment and field inhomogeneity, we have to complicate the analysis of distortions in sounding curves (Berdichevskii et al., 2009). Therefore, it is preferable to analyze the behavior of the electromagnetic-field components themselves. Note that the electromagnetic field in an arbitrary volume is fully determined by the distribution of electric- or magnetic-field tangential components on the surface; so, we can pass from analyzing the relationship between the field components on one site to analyzing the relationships between the distributions of the field components on the entire surface of the studied volume (Plotkin et al., 2008).

Let us consider an example of sounding an inhomogeneous medium (Fig. 1). The model consists of two inhomogeneous low-resistivity layers submerged in a homogeneous half-space with ρ = 1000 Ohm · m (Fig. 1, *a*, *b*):

$$r_{s1} = 25 + 25\exp\left\{-\left(\frac{x-360}{144}\right)^2 - \left(\frac{y-1215}{162}\right)^2\right\},$$
$$0 \le H \le 80,$$
$$\rho^{-1}(x, y, H) = 0.001 + 0.01\exp\left\{-\left(\frac{H-r_{s1}}{7}\right)^4\right\},$$
$$(6)$$
$$r_{s2} = 100 + 30\exp\left\{-\left(\frac{x-1080}{144}\right)^2 - \left(\frac{y-405}{162}\right)^2\right\},$$
$$40 \le H \le 190.$$
$$\rho^{-1}(x, y, H) = 0.001 + 0.02\exp\left\{-\left(\frac{H-r_{s2}}{30}\right)^4\right\},$$