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Results of inversion of distorted magnetotelluric sounding curves (*numerical experiment*)

V.V. Plotkin *

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

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Abstract

The paper presents the results of a joint inversion of magnetotelluric sounding (MTS) curves taken at several stations without preliminary selection and normalization and distorted by the presence of lateral electrical-conductivity inhomogeneities in the medium. In the calculations, we used synthetic MTS data for a three-dimensional model. Preparation and interpretation of data are carried out by the Trefftz method using a numerical model of the field and MTS curve distortions. To solve the inverse problem and optimize the subsurface model, we used a nonlinear least-squares method and an iterative process with calculation of the sensitivity matrix and its singular decomposition. The target functional is determined by the discrepancies between the model and synthetic experimental apparent-resistivity curves corresponding to the elements of the impedance tensors on the lateral diagonal. The reliability of the reconstructed subsurface model is characterized by the dispersion of the deviations of its parameters from the parameters of the known model used for the preparation of synthetic experimental data. The joint consideration of distorted apparent-resistivity curves at several stations increases the reliability of interpretation results. The obtained solution to the inverse problem is approximate and can be used as a starting model for more complex algorithms and programs.

Keywords: magnetotelluric sounding; distortion and interpretation of MTS curves; electrical conductivity; geoelectric section; Trefftz method

Introduction

The basic model for magnetotelluric sounding (MTS) is a horizontally layered earth excited by a vertically incident plane wave. Inversion of dependences of the apparent resistivity and impedance phases on sounding frequency (MTS curves) makes it possible to estimate the parameters of deep geoelectric sections.

In practice, MTS curves are often distorted due to the presence of lateral inhomogeneities in the earth. By distortions of MTS curves are meant their deviations from the curve corresponding to the horizontally layered section with the electrical conductivity dependent on the depth under the sounding station. Such distortions complicate the interpretation of experimental data. Neglect of possible distortions of the curves may lead to an inaccurate interpretation of MTS data on the deep structure of the earth.

Magnetotelluric sounding is usually based on profile measurements. The choice of profiles at a test site is motivated by the possibility of using well-elaborated two-dimensional and one-dimensional approximations for further processing of measurement data. The concept of three-dimensional subsurface structures provides agreement between the results obtained on several profiles.

This approach, in our opinion, involves laborious data processing (choice of appropriate MTS curves—longitudinal or transverse, minimum or maximum, distorted, undistorted, and methods of their normalization) and difficulties in the analysis of the results associated with verification of the conditions for the two-dimensionality of geoelectric structures. This is confirmed by some recent studies (Belyavsky, 2015; Belyavsky and Yakovlev, 2016; Moroz and Moroz, 2012; Moroz et al., 2016; Nevedrova et al., 2011). It is noted that all difficulties are caused by uncertainties in subsurface variations across the profile.

Of course, these drawbacks could be eliminated by switching to solution of the inverse MTS problem for a three-dimensional earth taking into account all recorded curves at stations on the ground. However, in practice, the solution of the inverse MTS problem for a three-dimensional earth has not yet been widely used because of the high computational cost. The more

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

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detailed the model used, the higher the computational cost (Persova et al., 2011). In essence, for MTS practice, it is important to find a balance between computational costs and the degree of approximation of the real earth and the reliability of interpretation results.

It is important that the contribution to the additions to the impedances at a sounding station from deeply and laterally remote three-dimensionally perturbed regions reduces. According to perturbation theory and numerical estimates, the dimensions of the zone of influence are of the order of a few skin-layer thicknesses (Plotkin, 2012, 2013). To account for the distortions of MTS curves at sounding stations due to the adjacent inhomogeneous medium, we have developed a numerical field model (Plotkin and Gubin, 2015) based on the Trefftz method (Egorov, 2011). It allows a significant reduction in the computational resources when using a cruder earth model. By changing the detail of subsurface mapping, one can try to find a compromise between the quality of interpretation of experimental data and computational costs. In this paper, we present the results of using the field model (Plotkin and Gubin, 2015) to solve the inverse MTS problem. The input data are MTS curves taken at a few stations without any selection and processing.

For reliable interpretation of the MTS results, it is preferred that the location of sounding stations should be adequate to the subsurface structure. The distance between the stations should provide an accurate recording of the spatial harmonics of the field due to lateral subsurface inhomogeneities (considering the aliasing effects according to the Kotel'nikov theorem). By analogy with time readings, sounding stations are preferably located (if terrain conditions allow) on a uniform grid whose dimensions determine the smallest scale with which details of the subsurface structure are determined from sounding results. In practice, another similar version with gaps is more suitable; it is considered below.

Numerical field model and data interpretation method

Synthetic MTS data for a three-dimensional earth were used. The preparation and interpretation of the data were carried out using a numerical model of the effect of subsurface and deep inhomogeneities over a one-dimensional layered geoelectric section (Plotkin and Gubin, 2015). Each of the several laterally inhomogeneous layers is represented by a set of parallelepipeds with uniform electrical conductivity. The boundary conditions take into account the excitation of the TM-mode and the spatial harmonics of the fields in the laterally inhomogeneous layers. The lower boundary conditions at the interface with the horizontally layered subsurface take into account the attenuation of the spatial harmonics of the field with depth in the subsurface. The upper boundary conditions on the ground take into account the attenuation of the spatial harmonics of the field with depth of the atmosphere and the field of the primary wave vertically incident on the medium. On the side faces of the computational volume containing lateral inhomogeneities, periodic boundary conditions are used. The dimensions of the test site are chosen so large that the lateral boundaries have a weak effect on the calculation results (Plotkin and Gubin, 2015).

The solution of the inverse problem was found from the data of several MTS stations by minimizing the following target functional:

$$\Phi = \frac{1}{2KJ}\sum_{k=1}^{K}\sum_{j=1}^{J}\left(\left|\frac{\rho_{xy}^{\mathrm{C}}-\rho_{xy}^{\mathrm{E}}}{\rho_{xy}^{\mathrm{E}}}\right|^{2}+\left|\frac{\rho_{yx}^{\mathrm{C}}-\rho_{yx}^{\mathrm{E}}}{\rho_{yx}^{\mathrm{E}}}\right|^{2}\right)_{k,j}+\lambda\sum_{i}m_{i}^{2},$$

where ρ_{xy}^{C}, ρ_{xy}^{E}, ρ_{yx}^{C}, and ρ_{yx}^{E} are the apparent resistivities (the subscripts xy and yx denote different polarizations of the field, and the superscripts C and E correspond to the values calculated for the current model and experimental values, respectively) at different stations (summation over k) and over different periods (summation over j). Here we take into account only the apparent-resistivity curves calculated from the elements of the impedance tensor on the lateral diagonal. The introduction of terms associated with the curves determined from the additional impedances and with phase curves (in the examples below) did not provide any advantages.

To optimize the subsurface model, we used a nonlinear least-squares method and an iterative process involving calculations of the sensitivity matrix and its singular-decomposition (Senkaya and Karsli, 2016). For stability and regularization of the process, the term $\lambda \sum_{i} m_i^2$ is added to the target functional, where m_i are the required parameters of the model and λ is a parameter whose magnitude determines the stability of the process. This parameter is chosen so as to provide minimum discrepancy for the next iteration. The obtained minimum of the target functional of discrepancies of apparent-resistivity curves at several stations determines the optimum model and its parameters m_i (electrical conductivities in laterally inhomogeneous layers and the thicknesses of these layers; more details are given below).

Calculation results and discussion

Recent interest has centered on the structure of active deep fluid-saturated faults. They form conductive channels in the high-resistivity lithosphere, which can be studied by MTS. These channels may have a complex structure and may not be described by two-dimensional structures (Plotkin et al., 2017). Therefore, to analyze the capabilities of the proposed approach, we used a subsurface model with various conductive channels.

Consider the results of calculations for a model represented by three layers with a resistivity of 100, 1000, and 100 Ohm·m (top down) and thicknesses of 0.7, 5, and 7 km, respectively, and an underlying layer with a resistivity of 20 Ohm·m. The entire second layer is penetrated by a vertically conductive channel with a resistivity of 20 Ohm·m and a horizontal section with dimensions of 5 × 15 km elongated along the *OY* axis (Fig. 1). It was assumed that MTS was carried out at a