# About Measurement of Vertical Component of Electric Field During Magnetotelluric Sounding

**Valery V. Plotkin and Vladimir S. Mogilatov**

**Abstract** In magnetotelluric sounding (MTS), variations of five components of electromagnetic field are usually registered. With the standard approach in experiment transfer functions are defined as ratios between horizontal components of electric and magnetic fields. Deviations from the Tikhonov-Cagniard basic model are defined by the fifth registered component—the vertical component of magnetic field. In order to increase the reliability of results obtained by the inversion and to gain more information from MTS, it is proposed to carry out the additional registration of vertical component of the electric field in the medium. At present, for registration of variations of vertical electric component the method of measurement of potential difference arising on the vertical line immersed in the sea is applied. On the land, for this purpose it is necessary to drill a hole or use already available wells, which may be difficult in practice. It is proposed to apply a circular electric dipole (CED) for registration of vertical electric component. Presently, CED is successfully used as an emitter in electromagnetic sounding methods. Its feature to excite in the layered medium a single TM-mode whose electric field has a vertical component, is used. In practice, CED is usually implemented with eight long radial lines. Taking into account this feature, CED can also be used as the MTS receiving system for registration of variations of a TM-mode field. Possibilities of using this schema in MTS are analyzed.

**Keywords** Magnetotelluric sounding · Vertical component of electric field · Circular electric dipole

## 1 Introduction

Variations of five components of electromagnetic field are usually registered during magnetotelluric soundings (MTS). It is connected with the fact that the MTS method

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is based on the Tikhonov-Cagniard model in a form of a horizontally-layered medium excited by the vertically falling plane wave. With the standard approach, transfer functions are determined in experiment as ratios between horizontal components of electric $E_{x,y}$ and magnetic fields $H_{x,y}$. Deviations from the Tikhonov-Cagniard basic model are defined by the fifth registered component—the vertical component of magnetic field $H_z$.

Since the electrical conductivity of the atmosphere $\sigma_a \sim 10^{-14}$ S/m is very small, and the condition of continuity of vertical current is satisfied, it turns out that on the Earth's surface the vertical component of electric field $E_z$ is close to zero, and there is no need for its registration.

However, in the real case the component $E_z$ becomes zero only at the boundary with the atmosphere, while gradually decreasing in the adjacent skin layer. Moreover, if a medium within this layer is anisotropic, the $E_z$ component may be non-zero even at the boundary, since the transverse current in this case does not necessarily coincide in direction with the $E_z$ component.

On the other hand, in order to determine the component $E_z$ or components $E_{x,y}$, in the field experiment the registration of potential differences for lines of finite length is carried out. It is possible to claim that anyway in practice the specified potential differences will always be non-zero and depend on the line length.

Considering, that in the process of solution of inversion problem for 3D medium the component $E_z$ for each actual model will also be determined, a comparison of the calculated values of $E_z$ with the experimental data is very desirable for higher reliability of the results. With a complex geoelectric structure of the medium and the presence of distortions in MTS curves, difficulties arise in interpreting the MTS data in practice. Unless possible distortions are taken into account, unreliable results of such an interpretation are quite likely: lateral near-surface heterogeneities can be perceived as deep "conductive" layers.

To eliminate these difficulties, various data processing algorithms and non-standard MTS options are being developed. Registration of vertical component $E_z$ could become one of those options. The other one proposed in [1] consists of the spatial averaging of electric field horizontal components by registration of these components with long lines along the studied profile (electromagnetic array profiling).

In this regard, it is interesting to analyze a possibility of registering the vertical component $E_z$ using the circular electric dipole (CED) located on the surface. The CED configuration was proposed in [2] as a power supply for the controlled-source electromagnetics (CSEM). At present, CED is successfully applied as an emitter in electromagnetic sounding methods [3], using its feature to excite only one TM-mode with the electric field having a vertical component in the horizontally layered medium. Since the magnetic field of TM-mode is equal to zero in the nonconductive atmosphere, registration of data on the Earth's surface eliminates the contribution of the direct field, and all observed variations of the magnetic field are associated only with deviations from the horizontally layered medium.

The ideal external current circuit and the real source are shown in Fig. 1. In practice, a CED is usually implemented with eight long radial lines. Considering the above-mentioned feature, CED can also be used as an MTS receiver for registration

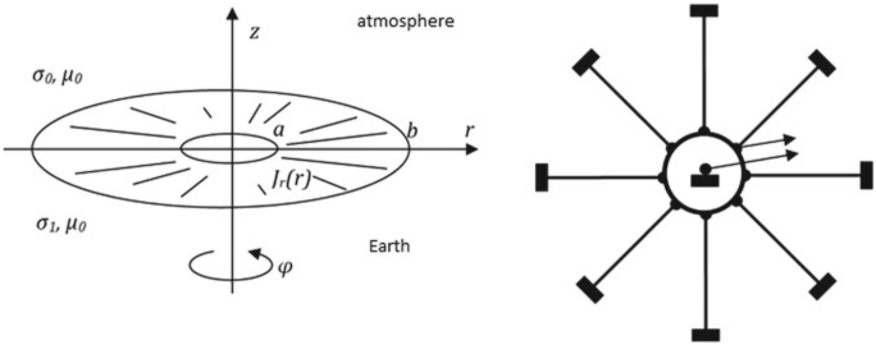


**Fig. 1** Ideal (on the left) and real (on the right) circular electric dipole on the Earth's surface

of variations of TM-mode field, namely, of the vertical component $E_z$ of electric field in the medium under the point of sounding. The method of measurement of potential difference on the vertical line immersed in a water reservoir is used for registration of $E_z$ variations [see, for example, 4, 5]. On the land, it is necessary to drill a hole for this purpose, or use already available wells, which may be impractical. Therefore, search for new ways to register $E_z$ is of great interest. The importance of obtaining new experimental results on the $E_z$ variations for many areas of geophysics should also be noted. Possibilities of using CED in MTS are analyzed in this article.

## 2 Results of Numerical Calculations of Potentials of $U_z$ and $U_{CED}$

It has been already established in [3] that when using CED as a source eight lines evenly distributed in azimuth are sufficient. To use CED as a receiver, it is necessary to define the ratio of potential differences registered on the vertical line in the medium $U_z$ and on the Earth's surface by means of CED $U_{CED}$. The CED radius is an important characteristic that in practice determines the ratio of these potential differences. Influence of various factors when using CED as the MTS receiver can be investigated using numerical modeling.

For numerical simulation, the field model based on the Trefftz method [6] considering distortions of MTS curves caused by the three-dimensional heterogeneity of the medium was used. We consider calculation results for the medium model presented by seven layers with resistivities of 25, 50, 100, 1000, 10, 1000 and 1 Ω m (from top to bottom) and thicknesses of 0.1, 0.1, 0.1, 15, 10, 45 and 15 km, respectively, and the underlying homogeneous subsurface of 100 Ω m (Fig. 2a). Such normal geoelectric section includes two conductive layers: the Earth's crust at depths of 15–25 km and the asthenosphere at depths of 70–85 km. Three near-surface layers with thickness of 0.1 km can be used to simulate MTS curve distortions. In particular, influence

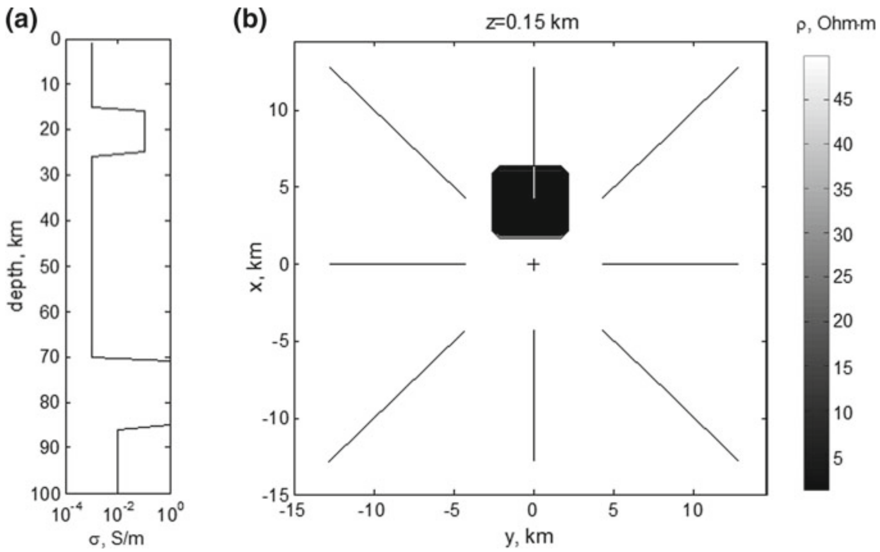


**Fig. 2** 3D model of the medium: the normal geoelectrical section (**a**), the horizontal section of second near-surface layer (**b**). CED radial lines on the Earth's surface are shown, the cross denotes its center

of a separate heterogeneity placed in the second layer from the surface (Fig. 2b) is studied here in detail.

It was assumed that MTS is carried out at the polygon with sizes of 30 × 30 km, with CED placed in its center. Their radial rays are shown in Fig. 2b by straight lines. When calculating using the numerical model based on the Trefftz method, each of seven medium layers is represented by 49 identical parallelepipeds with heights equal to the layer thickness and horizontal sections with sizes of 4.29 × 4.29 km (7 parallelepipeds along each of horizontal coordinate axes), in which the medium is uniform. In each parallelepiped, solutions of the Maxwell equations are used in the form of transverse counter propagating waves along each of coordinate axes. Considering the polarization of all waves, there are 12 such waves in each parallelepiped. All unknown amplitudes are solutions of the general system of equations obtained from conditions of matching tangential components of fields on all sides of the mentioned parallelepipeds and from boundary conditions. Using obtained wave amplitudes, we determine all components of the electromagnetic field in the centers of parallelepipeds and on the Earth's surface. Potential differences $U_z$ and $U_{CED}$ are determined further by integrals of the longitudinal component of electric field along vertical and radial registering lines respectively. To calculate all impedance tensor components, the calculations are repeated for two independent polarizations of vertical plane wave falling on the medium. Potential differences $U_z$ and $U_{CED}$ are also determined for each of two independent polarizations of primary wave. For this medium model we consider potential differences that are non-zero for chosen CED configuration, and correspond to the polarization of magnetic field of the primary wave along the *OY* axis with the amplitude of 1 nT.

In Fig. 3 the curves of apparent resistivity are shown obtained for the center of the polygon and the chosen medium model for two different resistivity values $\rho_n$ in a heterogeneity. As can be seen, in the presence of heterogeneity in the second layer of the medium from the surface (Fig. 2b) there are noticeable galvanic distortions. On the long time periods, the curves of the apparent resistivities $\rho_{xy}$ and $\rho_{yx}$ are also shifted along the ordinate axis relative to normal curve $\rho_l$. The more conductive the heterogeneity is, the greater this shift becomes.

Figure 4 shows the calculated dependences of potential differences $U_z$ and $U_{CED}$ on the time period in the center of the polygon (marked with the cross in Fig. 2b). Calculations were performed for different sets of values of lateral heterogeneity parameters: resistivity $\rho_n$, total longitudinal conductance $\Sigma_0$, characteristic scale $r_0$, volume conductivity $r_0^2\Sigma_0$ and distance $r_n$ from the center of heterogeneity to the CED center. Figure 4a displays changes in curves depending on resistivity values in a heterogeneity with identical other parameters. The greater are these deviations of resistivity in heterogeneity from background, the larger are values of potentials $U_z$ and $U_{CED}$.

Due to controlled differences in the real CED from the ideal (in quantity and lengths of radial lines), the shift between curves $U_z$ and $U_{CED}$ along ordinate axis appears. Curves obtained by removal of such offset over long time periods are displayed in Fig. 4a. For this purpose, all values of $U_{CED}$ curves are increased by a factor of 3.5. Note that this coefficient is the same for different resistivity values in the heterogeneity and under identical other conditions.

As can be seen, small differences between the $U_z$ and $U_{CED}$ curves remain for short time periods. This is confirmed by analyzing the data of ideal CED. With decreasing the distance to heterogeneity while preserving its volume conductivity $r_0^2\Sigma_0$, the coincidence of $U_z$ and $U_{CED}$ curves is also observed over an increased range of long

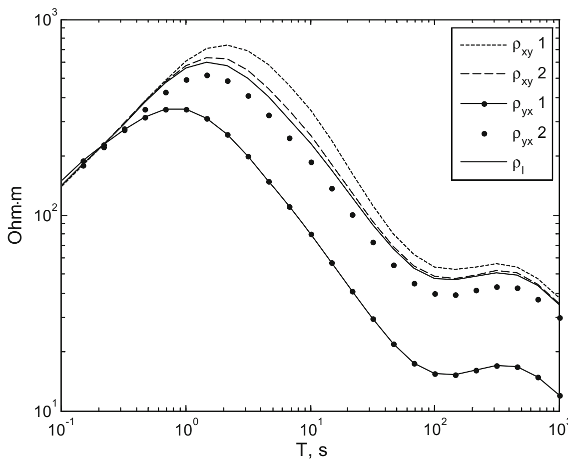


**Fig. 3** Curves of apparent resistivities $\rho_{xy}$ and $\rho_{yx}$ in the polygon center for two resistivity values $\rho_n$ in heterogeneity (1—$\rho_n = 1\ \Omega$ m, 2—$\rho_n = 10\ \Omega$ m, $\rho_l$—the normal curve for the background medium)

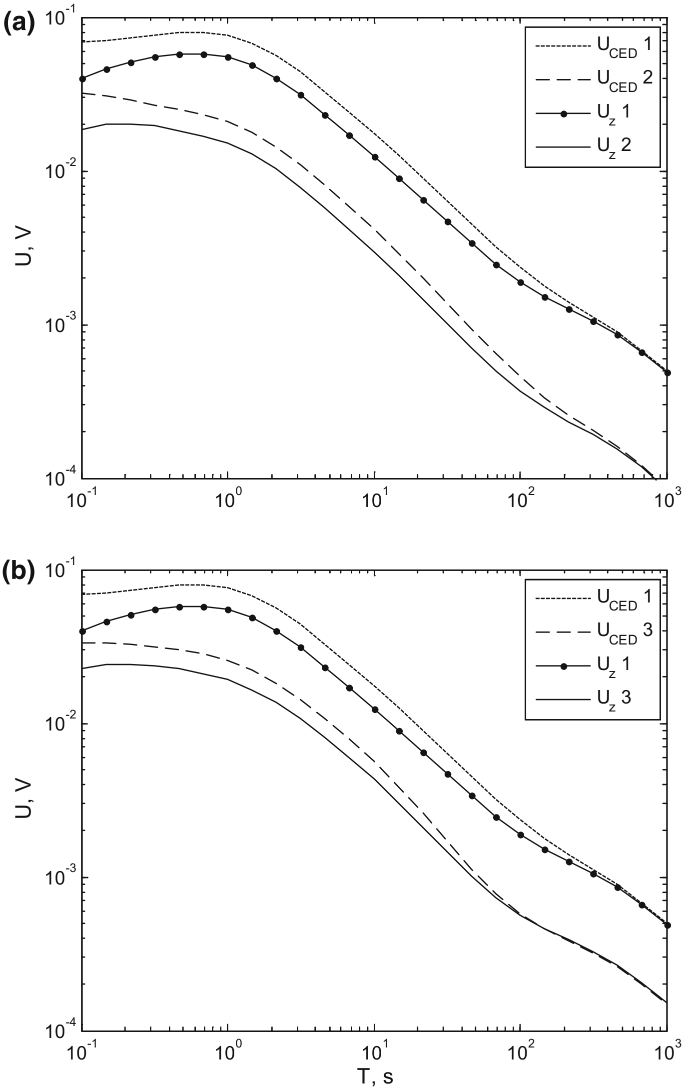


**Fig. 4** Curves of the potential differences arising on the vertical line in the center $U_z$ and totally on all CED radial lines $U_{CED}$ for different parameters of lateral heterogeneity: volume conductivity $r_0^2\Sigma_0$ and removal of center of heterogeneity from CED center $r_n$: **a** 1—$\rho_n = 1\ \Omega$ m, $r_n = 4.29$ km, $r_0^2\Sigma_0 = 1.84 \times 10^9$ Sm$^2$, 2—$\rho_n = 10\ \Omega$ m, $r_n = 4.29$ km, $r_0^2\Sigma_0 = 1.84 \times 10^8$ Sm$^2$; **b** 1—$\rho_n = 1\ \Omega$ m, $r_n = 4.29$ km, $r_0^2\Sigma_0 = 1.84 \times 10^9$ Sm$^2$, 3—$\rho_n = 1.1\ \Omega$ m, $r_n = 1.43$ km, $r_0^2\Sigma_0 = 1.84 \times 10^9$ Sm$^2$

periods (Fig. 4b). Curves for the case 3 were obtained in calculations with changes in parameters: for a 10 × 10 km polygon, the resistivity value in a heterogeneity $\rho_n = 1.1\ \Omega$ m and other equal conditions. The normalization coefficient for $U_{CED}$ curves for the case 3 turned out to be 1.12.

## 3 The Application of CED in the Arctic Region

Application of CED at its placement on the ice floe drifting in the Arctic is of interest. Because of nonconductive atmosphere, the medium excitation by TM-mode is excluded. The field recorded by CED is bounded only with 3D-inhomogeneities of the medium. To estimate CED application opportunities for MTS in the Arctic, we again carried out numerical calculations of the electromagnetic field by the Trefftz method [6]. Let us consider results of these calculations for the model of the medium presented in Fig. 5.

For the position of object and CED shown on Fig. 5, examples of results of calculation of the apparent resistivity and the vertical component of magnetic field are given in Fig. 6. Well conducting ocean shields manifestations of a target object in the behavior of magnetotelluric curves. Apparently, the object is shown in changes of apparent resistivity on the 100-th shares of percent. Variations of vertical component of magnetic field on day surface are also very small ~0.001 nT.

In Fig. 7 dependences of the potential of the TM-mode on different time periods, which are registered by the CED in its profile movement across the target, are given.

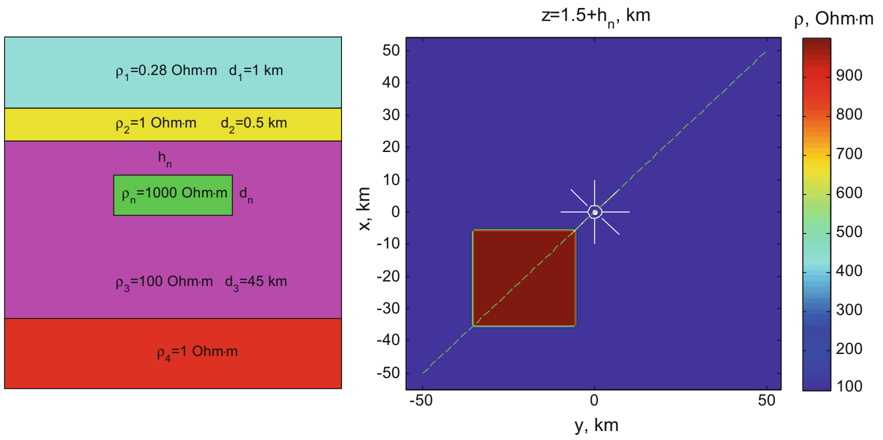


**Fig. 5** Geoelectrical section (on the left) and the plan of heterogeneity that is a target object under the ocean floor (on the right). In the center, there is CED shown white. Dotted line shows the profile along which it moves in drift. Values $\rho_1, d_1$ correspond to the sea water, $\rho_2, d_2$—to the sediments, $\rho_3, d_3$—to the crust, $\rho_4$—to the mantle and $\rho_n, d_n, h_n$—to the target object

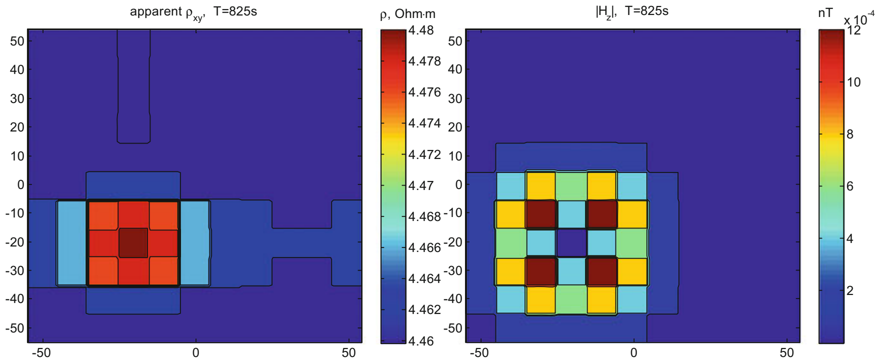


**Fig. 6** Maps of apparent resistivity (on the left) and vertical component of magnetic field (on the right) for the time period of T = 825 s. Object parameters are $d_n = 2$ km, $h_n = 2$ km

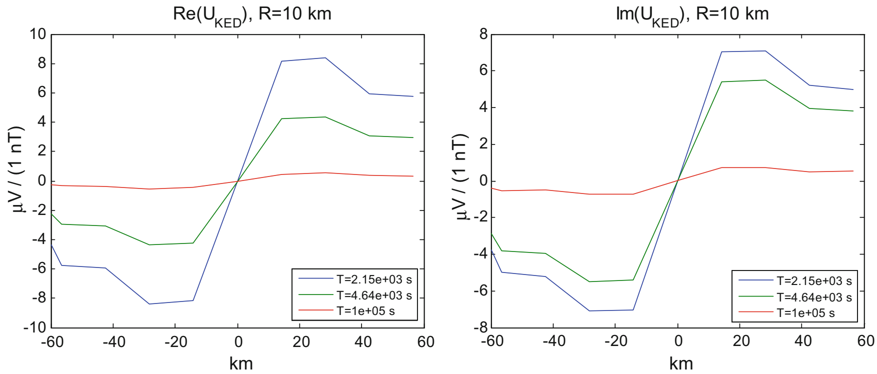


**Fig. 7** TM-mode potential for three periods registered by CED at different positions of its center concerning the target object

In the situation when the centers of the target and the CED coincide, the potential tends to zero, changing the sign upon the transition through this point on the profile.

Apparently, the CED can find the target with the increased specific resistivity under the ocean floor. It is clear that CED signal value depends on object parameters and its position relative to the center of installation.

## 4 Conclusion

In magnetotelluric sounding (MTS), variations of five components of electromagnetic field are usually registered. With the complex geoelectric structure of the medium and the presence of distortions in MTS curves, difficulties arise in practical interpretation of the MTS data. In order to increase the reliability of results obtained by inversion and to extract more information from MTS, it is proposed to carry out an additional registration of vertical component of the electric field in the medium applying a circular electric dipole (CED) for this purpose.

The potential difference registered by ideal CED completely coincides with the potential difference registered by the vertical line in the medium, if thickness of skin layer is much more than a characteristic size of lateral inhomogeneities (at low frequencies or long time periods). Similar situation takes place for galvanic distortions of MTS curve in the electrostatic field, which arise in a layer with lateral inhomogeneities. An application of CED allows to obtain the dependence of potential on the vertical line in the virtual well in the medium from the time period.

The numerical modeling of CED application in the case of near-surface inhomogeneities in the horizontally layered medium was carried out. Owing to controlled differences of real CED from ideal one (by quantity and lengths of radial lines), we observe a shift between curves of $U_z$ and $U_{CED}$ along the coordinate axes. The coefficient of the shift does not depend on the resistivity values in a heterogeneity under identical other conditions. After accounting for such shifts on the long time periods, small differences between $U_z$ and $U_{CED}$ curves still remain on the short time periods.

Thus, the potential difference measured by means of CED in the electric field excited in the 3D medium by a vertically falling incident plane wave is equivalent to the potential difference arising on the long vertical line in the CED center. In practice, it means an opportunity to register the potential difference along the vertical line without drilling the well necessary for it.

Targets with the increased specific resistivity under the ocean floor can be found by the CED installation.

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