Introduction

The radiomagnetotelluric (RMT) method is based on the use of electromagnetic (EM) fields of widely broadcasting radio transmitters in frequency band from 10 to 250-1000 kHz (Tezkan, 2008). Efficiency of this method in remote areas is limited by possibility to measure signals of very low frequency (VLF) radio transmitters with great long-range action only in 10-30 kHz band. In this case profiling investigations only are possible and the informative value of the method is considerably reduced. For these conditions the RMT method with own (controlled) source (CSRMT) is developed. In the CSRMT method a vertical loop (horizontal magnetic dipole) (Bastani, 2001) or a horizontal electric dipole (HED) (Simakov et al., 2010) are used as sources. CSRMT measurements and data analysis at high frequencies and great source-receiver separations require accounting of displacement currents in the earth and in the air. Last years T. Kalscheuer has investigated the influence of the displacement currents in the earth with regards to the RMT method (Kalscheuer et al., 2008). Features of the HED electromagnetic field with the consideration of influence of the displacement currents in the air are analyzed, the wave zone of the source is allocated and wave effects are described in this abstract.

Different zones at the electric dipole

Features of normal (above half-space) electric field components of HED are analyzed below. Magnetic field components have similar behavior. Expressions for the components E_x and E_y of HED on the air-earth boundary with the $e^{+i\omega t}$ time dependence are the follows:

$$E_x = \frac{Idl}{2\pi} \cdot i\omega\mu_0 \left[\frac{\partial^2}{\partial x^2} \int_0^\infty \frac{1}{k_0^2 n_1 + k_1^2 n_0} \cdot e^{n_1 z} J_0(mr) m dm - \int_0^\infty \frac{1}{n_0 + n_1} \cdot e^{n_1 z} J_0(mr) m dm \right]$$

$$E_y = \frac{Idl}{2\pi} \cdot i\omega\mu_0 \frac{\partial^2}{\partial x \partial y} \int_0^\infty \frac{1}{k_0^2 n_1 + k_1^2 n_0} \cdot e^{n_1 z} J_0(mr) m dm \qquad (1)$$

In this equations $k_j^2 = i\omega\mu_0 \left(\sigma_j + i\omega\varepsilon_j\right)$ - square of the wave number in j^{th} layer; $n_j = \sqrt{k_j^2 + m^2}$; $\sigma_j = 1/\rho_j$ – electric conductivity (S/m); ρ_j – electric resistivity (Ω·m), $\varepsilon_j = \varepsilon_j^{rel} 10^{-9} / 36\pi$ – absolute permittivity, ε_j^{rel}- relative permittivity, $\omega = 2\pi f$ – angular frequency, f - frequency (Hz), $r = \sqrt{x^2 + y^2}$ - source-receiver separation (m), J_0 – Bessel function of order 0, i – imaginary unit. All environments are nonmagnetic ($\mu_1 = \mu_0 = 4\pi \cdot 10^{-7}$ H/m).

In case of the quasi-static assumption ($k_0 = 0$, $k_1 = \sqrt{i\omega\mu_0\sigma_1}$) these expressions are simplified:

$$E_x = \frac{Idl\rho_1}{2\pi r^3} \cdot \left[3\cos^2\theta + (1 + k_1 r)e^{-k_1 r} - 2 \right]$$

$$E_y = \frac{3Idl\rho_1}{4\pi r^3} \cdot \sin 2\theta , \qquad (2)$$

where θ – angle between the HED moment and the source-receiver direction in the xy plane.

In electromagnetic soundings for controlled sources, particularly for HED, the quasi-static assumption is usually used and near-field, transition and far-field zones are allocated. In the **near-field zone** electric and magnetic field components are independent on frequency and have direct current features. In the **transition zone** field components are described by equations like (2). In the **far-field zone** (r/d>3-5, $d \cong 503\sqrt{\rho / f}$ – skin depth) the EM field can be approximated by the plane wave, so magnetotelluric approaches and software tools can be used here for the sounding curves inversion.

For powerful sources with the great long range action (hundreds and thousands kilometers) the **waveguide zone** has been allocated (Saraev and Kostkin, 1998), where the ionosphere and the displacement currents in the air influence on the EM field behavior. Features of waveguide effects are described in (Saraev and Shlykov, 2012).

In the CSRMT method electromagnetic fields are measured at relatively small distances (several kilometers from a source) and the influence of ionosphere is insignificant. At the same time the influence of displacement currents in the air is displayed very well just at distances of hundreds meters from a source. In this case in addition to the traditionally allocated in the EM practice near-field, transition and far-field zones a wave zone allocating is necessary. In the **wave zone** the EM field structure is dependent on the influence of displacement currents in the air. Previously allocated the waveguide zone can be considered as a partial case of the wave zone. The wave zones of different types sources are usually allocated at the consideration of radio waves propagation tasks according to the condition $r >> \lambda_0$, where r – source-receiver separation, λ_0 – EM wave length in the air (Kontorovich, 1956). In geophysical EM practice the wave zone in the radio physics sense was not usually used and features of EM field in this zone were not analyzed in detail.

Results of calculations

The forward 1D program has been developed for the calculation of the HED normal EM field with the account of displacement currents in both media (earth and air). Results of modeling are described below. Assume that the moment of HED is oriented along the horizontal axis x, current strength I = 1A, current frequency f = 100 kHz and dipole length dl = 100 m. For the air ρ_0=10^{14} Ω·m, ε_0^{rel} = 1, for the earth ρ_1 = 1000 Ω·m, ε_1^{rel} = 10.

Maps of $|E_x|$ и $|E_y|$ components isolines in the quasi-static assumption and with the account of displacement currents are shown in Figure 1. We can see sufficient difference of the electric field structure in the wave zone compare to the quasi-static case. Area of the $|E_x|$ minimum, orientated approximately at the angle of 45° to the dipole direction in the quasi-static case is smoothed and shifted to the dipole equator in the wave zone. Isolines of $|E_y|$ in the wave zone are extended along the direction orientated at the angle of 45° to the dipole moment.

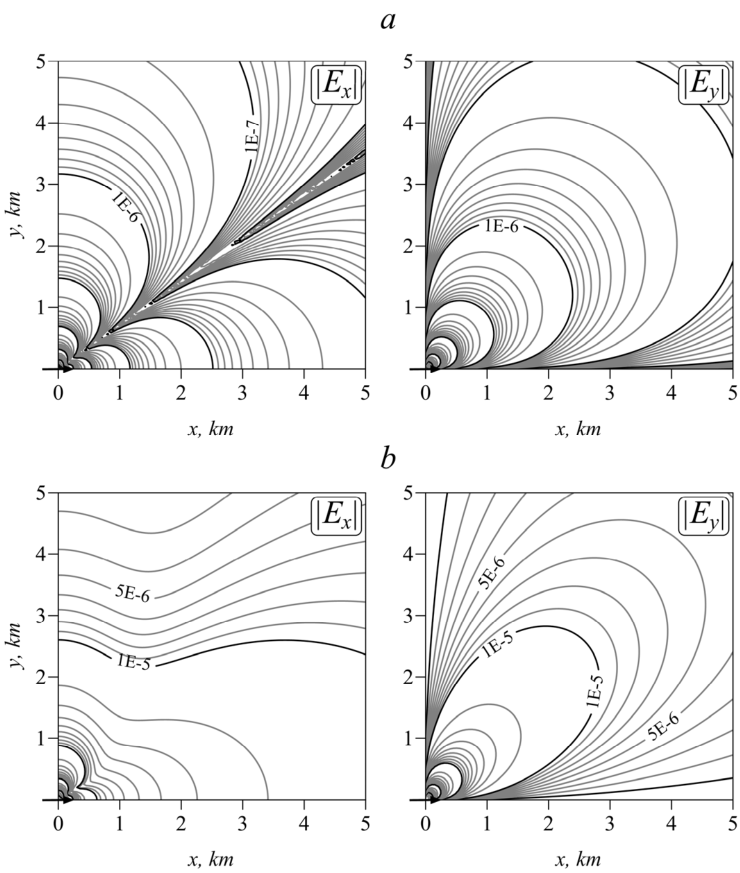

Figure 1: *Maps of isolines of the HED normal electric field horizontal components. a - quasi-stationary field, b – wave field.*

Directional diagram of HED in the wave zone is also changed (in Figure 2 normalized $|E_x|$ values are shown). For the quasi-static assumption $|E_x|$ in the equatorial area is in two times bigger than the same value along the dipole (Figure 2a). At the same time, in the wave zone $|E_x|$ in the axial area is much bigger than in the equatorial one (Figure 2c). Figure 2b shows an intermediate view of the directional diagram. This feature of the HED directional diagram was well known from the radio communications (Kontorovich, 1956) but it was not taken into account in the EM practice before.

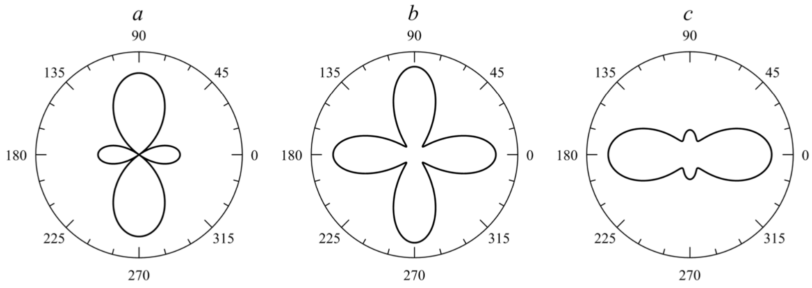

Figure 2: *Directional diagrams for the $|E_x|$ component at several distances from HED: a – 0.3 km, b – 1.1 km, c – 2 km.*

As it follows from Figures 1 and 2 the usually used for measurements of the surface impedance component Z_{xy} equatorial area in the wave zone becomes narrow. On the contrary, the axial area of HED becomes wide. Therefore, the selection of survey area in the CSRMT method should be fulfilled with the account of this feature. If the basic survey task is to study increased depths with the use of lower frequencies, the equatorial area is selected. For study of small depths with the use of higher frequencies the axial area is more favorable.

The parameter $\Delta|E| = 100\%\left(\left|E^{k_0\neq 0}\right| - \left|E^{k_0=0}\right|\right)/\left|E^{k_0\neq 0}\right|$ and the boundary value $\Delta|E|$ = 5% were used for allocation of the quasi-static zone (Figure 3). For the E_x component in the equatorial area the boundary between the quasi-static and wave zones corresponds to the induction number $|k_0|y$ = 0.33 (for the considered model this value corresponds to y = 160 m), in the axial area $|k_0|x$ = 1.0 (x = 460 m). For the E_y component the boundary corresponds to $|k_0|r$ = 0.45 (r = 200 m). The boundary positions are independent on the earth resistivity ρ_1.

In the quasi-static case the EM field of HED has the linear polarization. The influence of displacement currents in the air at a certain distance from the source causes the ellipticity of field polarization (Saraev et al., 1998). For the CSRMT method at f = 300 kHz and ρ_1 = 1000 Ω·m electric field polarization ellipse elements (big semi-axis a, small one b and big semi-axis rotation angle) were computed (Figure 4a). For obviousness reasons the values a and b were normalized on the a length (a = 1, b = b/a). In this case for the selected frequency the area of elliptically polarized field is quite wide. In addition, some delaying of ellipses big semi-axes directions relatively the linear polarization for the quasi-static case is observed. Area of the elliptically polarized field is coincided with the area of the $|E_x|$ minimum (Figure 4b).

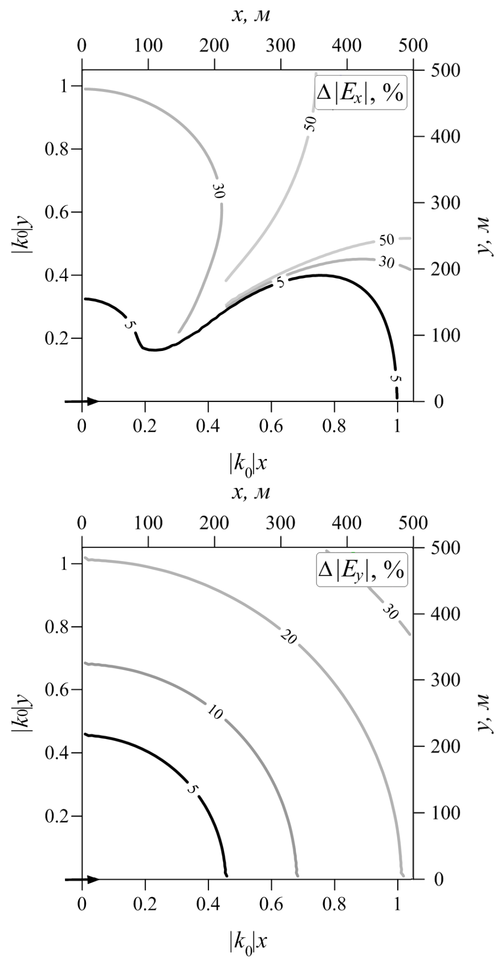

Figure 3: *Maps of relative deviation of quasi-static and wave electric field. Black line ($\Delta|E|$ = 5%) shows boundary between quasi-static and wave zones.*

Conclusions

The wave zone for HED as a source in the CSRMT method at the use of high frequencies (hundreds kilohertz) is allocated. In the wave zone the influence of displacement currents in the air should be taken into account and the EM field structure is sufficiently differed from the quasi-static case. The following features of the wave zone compare to the quasi-static one are noted: (1) slower EM field attenuation with distance, (2) changes of position of a favorable area for the CSRMT survey, (3) changes of the directional diagram with the maximum of radiation in the axial area, (4) appearance of the polarization ellipticity of EM field components and (5) delaying of ellipses big semi-axes relatively the linear polarization for the quasi-static case. In the wave zone the amplitude and phase of surface impedance is coincided with the plane wave impedance, therefore standard inverse MT software tools is steel applicable. Location of the boundary between the quasi-static and wave zones is independent on EM properties of the earth. For E_x and H_y components in the axial area it corresponds to the induction number $|k_0|x$ = 1.0, in the equatorial area - $|k_0|y$ = 0.33. For E_y и H_x components the boundary value $|k_0|r$ = 0.45.Existing of the polarization ellipticity for HED gives us a possibility to realize the tensor CSRMT survey with a single source of EM field only. Described features of the EM field in the wave zone of HED were confirmed by field experiments.

Acknowledgements

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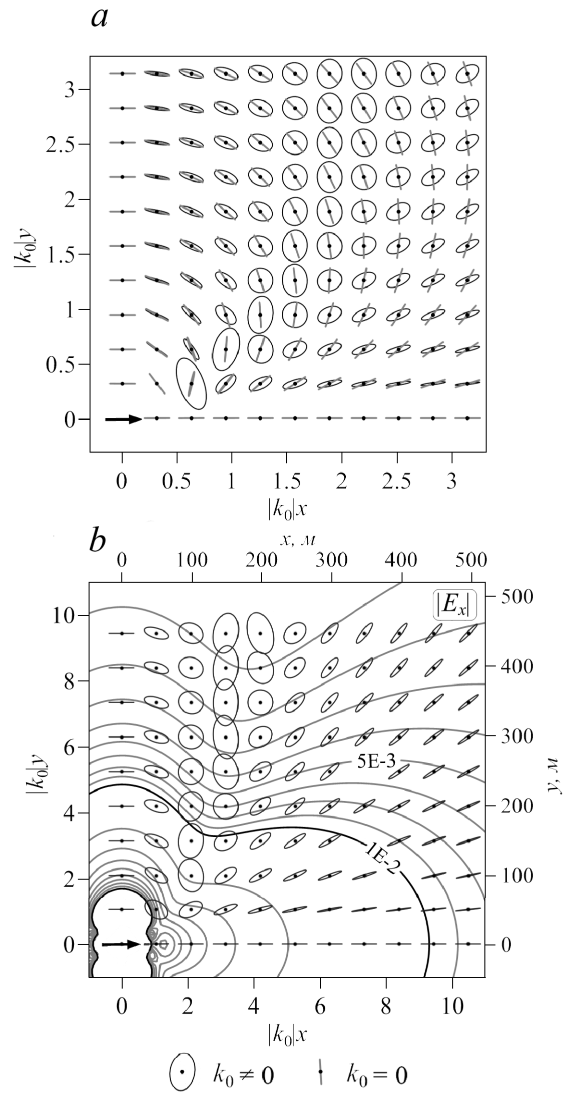

***Figure 4:** Polarization ellipses of the HED electric field in the wave zone (k ≠ 0) and in the quasi-static case (k = 0) (a) and the map of $|E_x|$ isolines combined with the electric field polarization ellipses (b).*

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