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Theoretical model of DC electric field formation in the ionosphere stimulated by seismic activity

V.M. Sorokin[a,*], V.M. Chmyrev[b], A.K. Yaschenko[a]

[a] *Institute of Terrestrial Magnetism, Ionosphere and Radiowave Propagation (IZMIRAN), Russian Academy of Sciences, 142190 Troitsk, Moscow Region, Russian Federation*
[b] *Institute of the Earth Physics, Russian Academy of Sciences, Moscow, Russian Federation*

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Abstract

Seismic activity is accompanied by emanation of soil gases into the atmosphere. These gases transfer positive and negative charged aerosols. Atmospheric convection of charged aerosols forms external electric current, which works as a source of perturbation in the atmosphere–ionosphere electric circuit. It is shown that DC electric field generated in the ionosphere by this current reaches up to 10 mV/m, while the long-term vertical electric field disturbances near the Earth's surface do not exceed 100 V/m. Such a limitation of the near-ground field is caused by the formation of potential barrier for charged particles at the Earth's surface in a process of their transport from soil to atmosphere. This paper presents the method for calculation of the electric field in the atmosphere and the ionosphere generated by given distribution of external electric current in the atmosphere.

Keywords: Ionosphere; Earthquake; Electric field; External current; Charged aerosols; Convective transport

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1. Introduction

Recent experimental and theoretical studies of pre-earthquake processes in the lithosphere, atmosphere and the ionosphere of the Earth display an existence of wide class of electromagnetic (EM) signals generated at different stages of earthquake development (Buchachenko et al., 1996). These so-called EM precursory signals include ULF magnetic field variations, seismic electric signals, anomalies in subionospheric VLF/LF propagation, bursts of pulse-like VLF emissions, ELF radiation correlated with plasma density irregularities in the ionosphere, disturbances of DC electric field both in the ionosphere and the atmosphere, etc. (see the most recent review by Varotsos (2001) and references therein). The present paper concerns only one of these phenomena—DC electric field in the atmosphere–ionosphere coupled system. Sorokin et al. (2001a) and Sorokin and Chmyrev (2002) have formulated the electrodynamic model of ionospheric precursors to earthquakes. This model gives an explanation to some electromagnetic and plasma phenomena connected with earthquake by the amplification of DC electric field in the ionosphere over a seismic region. To initiate these phenomena the electric field should reach up to 10 mV/m. Such electric fields were reported from satellite observations both over earthquake and hurricane regions (Chmyrev et al., 1989; Isaev et al., 2002). Possible connection of atmospheric electric field with seismic activity and the mechanisms of penetration of atmospheric field into the ionosphere

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[*] Corresponding author. Tel.: +7 95 3309902; fax: +7 95 3340124.
E-mail address: sova@izmiran.ru (V.M. Sorokin).

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were studied by Pierce (1976), Pulinets et al. (1994), Molchanov and Hayakawa (1996) and Boyarchuk et al. (1998). The calculation made in these papers show that the electric field in the ionosphere can reach 0.1–1.0 mV/m if vertical component of the field at the Earth surface exceeds 1–10 kV/m at the horizontal scale from 10 to 100 km. The ground-based observations have shown an existence of short-term (<1 h) seismic-related vertical electric field disturbances with magnitudes up to 1000 V/m, while the long-term (1–10 days) electric field perturbations exceeding ~100 V/m within earthquake areas at distances from tens to few hundreds km from the epicenter have not been observed (Vershinin et al., 1999). This contradiction between satellite and ground-based measurements of long-term vertical DC electric field disturbances can be reconciled by the consideration of the effects of external electric current in the atmosphere, as will be carried out in present paper.

Sorokin and Yaschenko (2000) and Sorokin et al (2001a, b) have constructed the theoretical model of the electric field disturbances caused by the conductivity currents in the atmosphere and the ionosphere initiated by external electric current. According to this model, external current arises as a result of emanation of charged aerosols transported into the atmosphere by soil gases and subsequent processes of upward transfer, gravitational sedimentation and charge relaxation. So the time scales of variations of the external currents and the injection of soil gases should be similar. Seismic-induced emanation enhancement of soil gases and accompany elements is observed during days or week before earthquake (Alekseev and Alekseeva, 1992; Pulinets et al., 1994; Virk and Singh, 1994; Heincke et al., 1995). The model estimate of ionospheric electric field caused by pre-earthquake processes give the magnitude ~10 mV/m (Sorokin et al., 2001a). Further development of this model includes a new method for calculation of the electric field in the atmosphere and the ionosphere and the mechanism for limitation of vertical electric field near the Earth surface is given below.

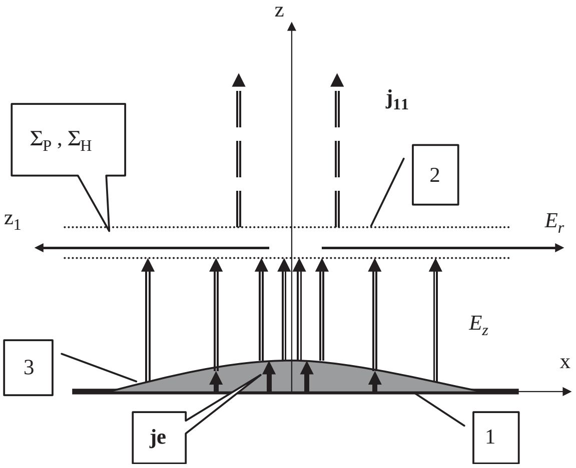

Fig. 1. Scheme of the model used for calculations of current and field in the atmosphere–ionosphere electric circuit. 1, The Earth surface, 2, ionosphere, 3, zone of upward convection of charged aerosols.

2. Equation for the electric field potential

Let us consider generation of the electric field by external current $\mathbf{j}_e$ in the Earth–ionosphere layer. We will derive the equations for potential φ of the electric field disturbance $\mathbf{E} = -\nabla\varphi$. Let us introduce the Cartesian co-ordinates (x, y, z) with the axis z directed vertically upward parallel to homogeneous magnetic field and with the origin located on the absolutely conductive Earth's surface (see Fig. 1). We assume that the electric field potential on this surface is $\varphi|_{z=0} = 0$. The atmosphere characterized by the conductivity $\sigma(z)$ is located in the layer $0<z<z_1$. Electric potential in this region is derived from the equation of continuity and the Ohm's law:

$$\nabla(\mathbf{j} + \mathbf{j}_e) = 0, \quad \mathbf{j} = \sigma\mathbf{E} = -\sigma\nabla\varphi$$

and satisfies the following equation:

$$\frac{\partial^2\varphi}{\partial z^2} + \frac{1}{\sigma(z)}\frac{d\sigma(z)}{dz}\frac{\partial\varphi}{\partial z} + \Delta_\perp\varphi = \frac{1}{\sigma(z)}\nabla\mathbf{j}_e. \tag{1}$$

Plane $z = z_1$ coincides with thin ionosphere characterized by the tensor of integral conductivity with the components Σ_P and Σ_H—Pedersen and Hall conductivity, respectively. Integrating the equation of current continuity in the ionosphere $\nabla \cdot \mathbf{j} = 0$ on its width gives the boundary condition:

$$j_z(z_1 + 0) - j_z(z_1 - 0) = \Sigma_P \Delta_\perp \varphi_1, \tag{2}$$

where $\varphi_1 = \varphi(z_1)$. Since in quasi-static approximation the geomagnetic field lines in the magnetosphere are equi-potential in the distribution of the electric potential in the ionosphere and the magnetic field-aligned current on its upper boundary are transported into magnetically conjugate region without changes. Field-aligned electric current flowing in the magnetosphere is closed by transverse conductivity currents in the conjugate ionosphere and the atmosphere. The boundary condition on the conjugate ionosphere is similar to Eq. (2), while the equation for potential in the conjugate atmosphere coincides with (1) at $\mathbf{j}_e = 0$. Let the altitude dependence of atmospheric conductivity has the form:

$$\sigma(z) = \sigma_0 \exp(z/h), \tag{3}$$

the external current is directed upward and has symmetric distribution relative to the z-axis: $j_e = j_e(z, r)$, where $r = \sqrt{x^2 + y^2}$. Applying Gankel