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DC electric field amplification in the mid-latitude ionosphere over seismically active faults

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Abstract. DC electric field in the ionosphere above seismically active regions can be formed in a process of external current insertion into the atmosphere-ionosphere electric circuit. This current arises as a result of convective upward transport of charged aerosols and their gravitational sedimentation. Aerosols are injected into the atmosphere by soil gases intensified in the zones of active faults. In general case the horizontal distribution of injected aerosols in such zones is asymmetric. In this report we propose the method for computation of DC electric field generated in the ionosphere and the atmosphere by external electric current with arbitrary spatial distribution. Oblique magnetic field and the conjugate ionosphere effects are taken into consideration.

1 Introduction

According to recent investigations there is a wide class of electromagnetic and ionospheric disturbances generated at different stage of seismic activity development in the faults. Results of these investigations were presented in the most recent monographs by Hayakawa (1999), Hayakawa and Molchanov (2002), review by Varotsos (2001) (see also references therein). In the present paper we consider only one of these phenomena – DC electric field formation in the ionosphere over seismically active faults. Sorokin et al. (2001a) and Sorokin and Chmyrev (2002) have formulated the electrodynamic model of atmosphere-ionosphere coupling. This model gives an explanation to some electromagnetic and plasma phenomena connected with amplification of DC electric field in the ionosphere. To initiate these phenomena the electric field should reach up to 10 mV/m. Such electric fields have been reported from satellite observations both over seismic 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 were studied by Pierce (1976), Pulinets et al. (1994), Molchanov and Hayakawa (1996), Boyarchuk et al. (1998) and Rapoport et al., (2004). 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. The model estimate of ionospheric electric field caused by pre-earthquake processes gives the magnitude $\sim$10 mV/m (Sorokin et al., 2001a). The method developed in (Sorokin et al., 2005a, b) allows to calculate electric field generated by axially symmetric external current. Further development of this model including new method for computation of the electric field in the atmosphere and the ionosphere over active faults with arbitrary spatial distribution of external current in oblique magnetic field is given below.

2 The electric field potential in the ionosphere

Let us find the horizontal distribution of conductivity current in the ionosphere generated by external electric current located in the near ground atmosphere. We will use the Cartesian co-ordinates (x, y, z) with z-axis directed vertically upward and x-axis lying in magnetic meridian plane, α is the magnetic field inclination. Plane z=0 coincides with absolutely conductive Earth's surface. The model used for calculations of current and field in the atmosphere-ionosphere electric circuit is presented in Fig. 1. Distribution of vertical

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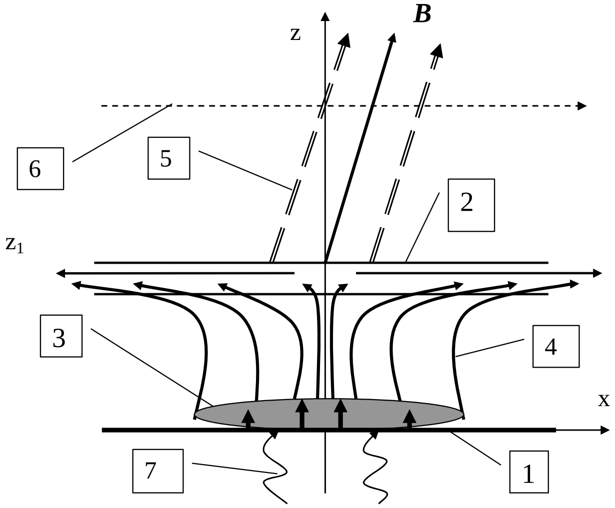

Fig. 1. The model used for calculations of current and field in the atmosphere-ionosphere electric circuit above seismically active faults. 1. Earth surface, 2. Conductive layer of the ionosphere, 3. External electric current in the lower atmosphere above seismically active faults, 4. Conductivity electric current in the atmosphere-ionosphere circuit, 5. Field-aligned electric current, 6. Satellite trajectory, 7. Charged aerosols injected into the atmosphere by soil gases.

component of external current in horizontal plane (x, y) is determined by the function $j_e{=}j_e(x, y, z{=}0)$, the electric field is given by $\mathbf{E}{=}{-}\nabla\varphi$ and $\sigma(z)$ denotes the atmosphere conductivity in the layer $0{<}z{<}z_1$. We assume that the electric field potential φ is zero on the Earth surface. Its distribution in the atmosphere is derived from the current continuity equation and the Ohm's law and satisfies the following equation:

$$\frac{d}{dz}\left[\sigma(z)\frac{d\varphi}{dz} - j_e(x, y, z)\right] = 0\,. \tag{1}$$

This equation is true in the case when the horizontal scale of external current exceeds the characteristic vertical scale of atmospheric conductivity variations. Plane $z{=}z_1$ coincides with thin conductive ionosphere characterized by integral conductivity tensor. In quasi-static approximation the magnetic field lines in the magnetosphere are equipotential. Consequently the distributions of electric field potential in the ionosphere and the field-aligned current on its upper boundary are transferred into the magnetically conjugate region without changes. The field-aligned current flowing in the magnetosphere is closed by the conductivity current in the conjugate ionosphere and atmosphere. The boundary condition at $z{=}z_1$ can be found by integration of the current continuity equation over the conjugate regions of the ionosphere (Sorokin et al., 2005a, b):

$$\begin{aligned}
&\left.\left(\sigma\frac{d\varphi}{dz}\right)\right|_{z=z_1-0} = 2\Sigma_P\left(\frac{1}{\sin^2\alpha}\frac{\partial^2\varphi_1}{\partial x^2} + \frac{\partial^2\varphi_1}{\partial y^2}\right) - \frac{\varphi_1}{\rho};\\
&\varphi_1(x, y) = \varphi(x, y, z = z_1); \quad \rho = \int_0^{z_1}\frac{dz}{\sigma(z)};\\
&\left.\left(\sigma\frac{d\varphi}{dz}\right)\right|_{z=z_1-0} = \sigma(z = z_1 - 0)\left.\frac{d\varphi}{dz}\right|_{z=z_1-0}\\
&= -j(x, y, z = z_1 - 0) = -j_1(x, y)\,,
\end{aligned} \tag{2}$$

where: $\varphi_1(x, y)$ is the electric field potential distribution in the ionosphere, Σ_P is the Pedersen's integral conductivity of the ionosphere,$\sigma(z{=}z_1{-}0)$ is the atmospheric conductivity at the lower edge of the ionosphere, $j_1(x, y)$ is the conductivity electric current on the lower edge of the ionosphere inflowing from the atmosphere. This distribution is connected with horizontal component of the electric field and the conductivity current flowing in the ionosphere. Solution of Eq. (1) satisfying the boundary condition $\varphi|_{z=0}{=}0$ has a form:

$$\begin{aligned}
&\varphi(x, y, z) = \int_0^z \frac{j_e(x,y,z')}{\sigma(z')}dz' - j_1(x, y)\int_0^z \frac{dz'}{\sigma(z')};\\
&j_1(x, y) = \frac{\varepsilon(x,y)-\varphi_1(x,y)}{\rho}; \quad \varepsilon(x, y) = \int_0^{z_1}\frac{j_e(x,y,z)}{\sigma(z)}dz\,.
\end{aligned} \tag{3}$$

In this equation ε and ρ mean the electromotive force of external current and the electrical resistance of unitary area column between the ground and the ionosphere. Using the solution (Eq. 3) and the boundary condition (Eq. 2) yields approximate equation for electric potential distribution $\varphi_1(x, y)$ in the ionosphere:

$$\left(\frac{1}{\sin^2\alpha}\frac{\partial^2}{\partial x^2} + \frac{\partial^2}{\partial y^2}\right)\varphi_1(x, y) = -\frac{j_1(x, y)}{2\Sigma_P}, \tag{4}$$

where α is the magnetic field inclination. At $\alpha{=}\pi/2$ this expression coincides with 2D Poisson equation. Spatial scale of the ionosphere potential distribution depends on the slope of geomagnetic field. Equations (3) and (4) are applicable for calculation of the electric fields induced by external current over seismically active faults with arbitrary distribution in horizontal plane and for any altitude dependence of the atmosphere electric conductivity in oblique magnetic field.

3 The vertical electric field limitation on the Earth's surface

Let us assume that the external electric current over fault is formed by superposition of currents arising from the injection of positive and negative charged aerosols into the atmosphere:

$$\begin{aligned}
&j_e(x, y, z) = j_p(x, y)s_p(z) - j_n(x, y)s_n(z);\\
&s_p(z = 0) = s_n(z = 0) = 1,
\end{aligned} \tag{5}$$

Functions $s_p(z)$, $s_n(z)$ denote the altitude distributions of external currents. Substitution of Eqs. (5) in (3) yields:

$$\begin{aligned}
&j_1(x,y) = \frac{1}{\rho}\left[j_p(x,y)k_p - j_n(x,y)k_n\right];\\
&E_{z0}(x,y) = \frac{1}{\sigma_0}\left[j_1(x,y) - j_p(x,y) + j_n(x,y)\right];\\
&k_{p,n} = \int\limits_0^{z_1} dz\frac{s_{p,n}(z)}{\sigma(z)};\quad E_{z0}(x,y) = E_z(x,y,z=0);\\
&\sigma_0 = \sigma(z=0).
\end{aligned} \tag{6}$$

Large magnitude (up to 1 kV/m) pre-earthquake vertical electric field disturbances on the Earth surface have characteristic temporal scale less or of the order of 1 h. At the same time the atmospheric electric field variations with typical scale exceeding 1 day at the distances within tens to hundreds km from earthquake center during seismically active period never exceed the background magnitudes ∼10-100 V/m. The mechanism of feedback between disturbances of vertical electric field and the causal external currents near the Earth surface can explain such limitation (Sorokin et al., 2005a). The feedback is caused by the formation of potential barrier on the ground-atmosphere boundary at the passage of upward moving charged aerosols through this boundary. Their upward transport is performed due to viscosity of soil gases flowing into the atmosphere. If for example positively charged particle goes from ground to the atmosphere, the Earth surface is charged negatively. The excited downward electric field prevents of particle penetration through the surface. At the same time this field stimulates the going out on the surface of the negatively charged particles. In a presence of such coupling the magnitudes of external currents on the Earth surface depend on vertical component of the electric field on the surface. External currents of positive and negative charged aerosols depend on the vertical component of electric field on the Earth's surface accounting for feedback mechanism:

$$\begin{aligned}
&j_p(x,y) = j_{p0}(x,y)f(E_{z0}(x,y)/E_{cp});\\
&j_n(x,y) = j_{n0}(x,y)f(-E_{z0}(x,y)/E_{cn}),
\end{aligned} \tag{7}$$

where $j_{p0}(x,y)$, $j_{n0}(x,y)$ are determined by the injection intensity of aerosols in missing of the electric field influence. Critical fields E_{cp}, E_{cn} may be estimated from the balance between viscosity, gravity and electrostatic forces. Viscosity force connected with elevated soil gases acts in upward directed. Gravity force is directed downward. Electrostatic force connected with going out of positive particle is directed downward.

$$eZ_pE_{cp}=6\pi\eta R_pV-m_pg;\quad eZ_nE_{cn}=6\pi\eta R_nV-m_ng, \tag{8}$$

where eZ_p, eZ_n are the positive and the negative charge of aerosol particles correspondingly, η is the air viscosity coefficient, V is the velocity of elevation of soil gases within ground, $R_{p,n}$ are the radii of aerosol particles, $m_{p,n}=(4/3)\pi R_{p,n}^3\mu$ are the particle masses and μ is their number density. The term in left part of Eqs. (8) is electrostatic force. First term in the right part of Eqs. (8) is viscosity force and second term in the right one is gravity force. For simplicity we will assume that the aerosols of opposite signs consist from the same particles ($E_{cp}=E_{cn}=E_c$). For further calculations we select $f(E_{z0}/E_c)$ in a modeling form $f=\sqrt{1+E_{z0}/E_c}$. Such form of function $f(E_{z0}/E_c)$ qualitatively characterizes the electric field effect to the external current. Substitution of this function in Eqs. (4) and (6) yields:

$$\begin{aligned}
&E_{z0}(x,y) = \frac{1}{\sigma_0}\left[j_{p0}(x,y)\left(\frac{k_p}{\rho}-1\right)\right.\\
&\left.\sqrt{1+\frac{E_{z0}(x,y)}{E_c}} - j_{n0}(x,y)\left(\frac{k_n}{\rho}-1\right)\sqrt{1-\frac{E_{z0}(x,y)}{E_c}}\right].
\end{aligned} \tag{9}$$

This equation allows calculating the vertical electric field component on the Earth surface at the given values of $j_{p0},\ j_{n0}$. Solution of Eq. (7) allows us to obtain the horizontal distribution of conductivity current on lower edge of the ionosphere inflowing from the atmosphere with accounting the feedback mechanism in following form:

$$\begin{aligned}
&j_1(x,y) = \frac{1}{\rho}\left[j_{p0}(x,y)\sqrt{1+\frac{E_{z0}(x,y)}{E_c}}k_p\right.\\
&\left.-j_{n0}(x,y)\sqrt{1-\frac{E_{z0}(x,y)}{E_c}}k_n\right].
\end{aligned} \tag{10}$$

4 DC electric field calculation

Horizontal distribution of the electric field potential in the ionosphere is derived from Eq.(4). Transferring of the independent variables from (x,y) to $(\xi = x\sin\alpha, y)$ in this equation leads to 2D Poisson equation, which is solved by Green function method. This solution in variables (x,y) has a form:

$$\begin{aligned}
&\varphi_1(x,y) = -\frac{1}{4\pi\Sigma_P}\int\limits_{-\infty}^{\infty}\int\limits_{-\infty}^{\infty}\\
&G(x-x',y-y')j_1\left(x',y'\right)dx'dy'\cdot\\
&G(x,y) = \sin\alpha\ln\sqrt{x^2\sin^2\alpha+y^2}
\end{aligned} \tag{11}$$

The components of electric field in the ionosphere are determined by formulas:

$$E_x(x,y)=-\partial\varphi_1(x,y)/\partial x;\ E_y(x,y)=-\partial\varphi_1(x,y)/\partial y. \tag{12}$$

Substituting expressions (11) to (12) we obtain horizontal components of DC electric field in the ionosphere:

$$\begin{aligned}
&E_x(x,y)\\
&=\frac{1}{4\pi\Sigma_P}\int\limits_{-\infty}^{\infty}\int\limits_{-\infty}^{\infty}K_x(x-x',y-y')j_1\left(x',y'\right)dx'dy';\\
&E_y(x,y)\\
&=\frac{1}{4\pi\Sigma_P}\int\limits_{-\infty}^{\infty}\int\limits_{-\infty}^{\infty}K_y(x-x',y-y')j_1\left(x',y'\right)dx'dy';\\
&K_x(x,y)\\
&=\frac{x\sin^3\alpha}{x^2\sin^2\alpha+y^2};\quad K_y(x,y)=\frac{y\sin\alpha}{x^2\sin^2\alpha+y^2}.
\end{aligned} \tag{13}$$

Equations (9), (10) and (13) were used for computation of horizontal distribution of the electric field in the ionosphere

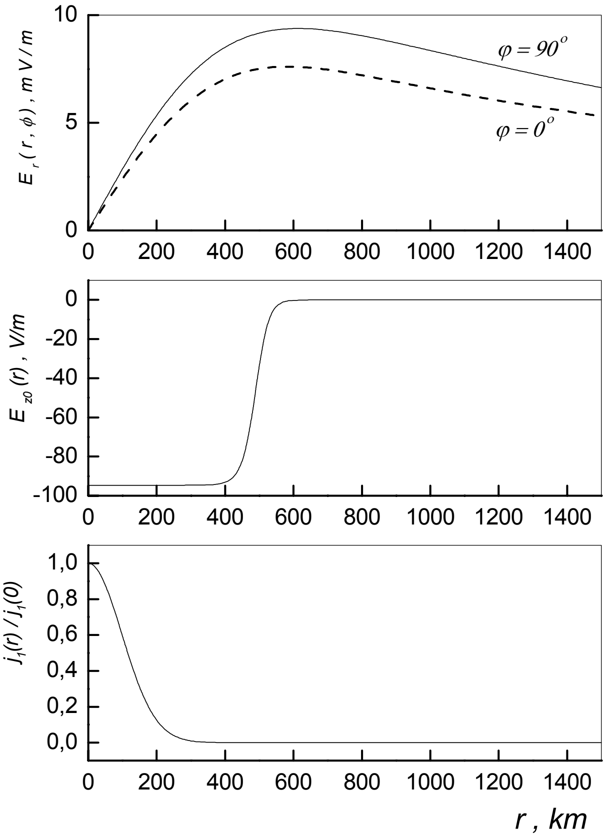

Fig. 2. Radial dependence of DC electric field calculated for the angle β=45° of orientation of the fault axis relatively to magnetic meridian plane. Upper panel: Horizontal DC electric field in the ionosphere within (φ=0°) and across (φ=90°) the plane of magnetic meridian. Angle of magnetic field inclination is 20°. Middle panel: Vertical component of DC electric field on the Earth surface. panel: Normalized vertical component of external current on the Earth surface.

and on the ground at different angles $\alpha$of inclination of the magnetic field and angles of orientation of the fault axis relatively to magnetic meridian plane. For the numerical calculations we assume that the model spatial distribution of external currents on the Earth's surface over fault is given by:

$$\begin{aligned}
&j_{p0}(x,y)=J_p\Phi(x,y);\; j_{n0}(x,y)=J_n\Phi(x,y);\\
&\Phi(x,y)=\exp\left(-p_1x^2-p_2y^2-p_3xy\right);\; J_n=0.67J_p;\\
&p_1=\left(\frac{\cos\beta}{a}\right)^2+\left(\frac{\sin\beta}{b}\right)^2;\; p_2=\left(\frac{\sin\beta}{a}\right)^2+\left(\frac{\cos\beta}{b}\right)^2;\\
&p_3=\sin(2\beta)\left(\frac{1}{a^2}-\frac{1}{b^2}\right)
\end{aligned} \tag{14}$$

where β is the angle of orientation of the fault axis relatively to magnetic meridian plane, a, b are the spatial scales of external current along and across the fault axis. We also assume $s_{p,n}=\exp(-z/h_{p,n})$; $\sigma(z)=\sigma_0\exp(z/h)$ and $k_{p,n}/\rho=h_{p,n}/(h+h_{p,n})$. According to (Sorokin and Yaschenko, 2000; Sorokin et al., 2001a, b) the external current in epicenter of charge aerosols injection area on the Earth's surface is determined by:

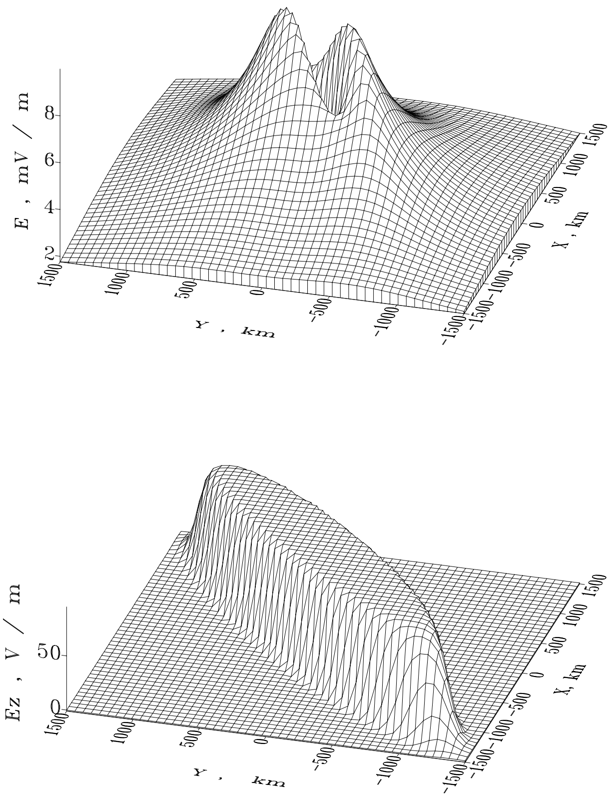

Fig. 3. Spatial distributions of DC electric field calculated for the angle β=45° of orientation of the fault axis relatively to magnetic meridian plane. Upper panel: Horizontal component of DC electric field in the ionosphere. Angle of magnetic field inclination is 20°. Lower panel: Vertical component of DC electric field on the ground.

$$J_p = 4\pi\sigma_0 eZ_p h_p N_{p0}\,, \tag{15}$$

where eZ_p is the positive charge of aerosol particle and N_{p0} is the aerosols number density. For numerical calculations we select the following parameters:

$$\begin{aligned}
&h_p = 20\,\text{km},\; h_n = 15\,\text{km},\; h = 5\,\text{km},\\
&a = 500\,\text{km},\; b = 100\,\text{km},\; N_{p0} = 2\times10^4\,\text{cm}^{-3},\\
&Z = 100,\; \sigma_0 = 2\times10^{-4}\text{s}^{-1},\; \Sigma_P = 2\times10^{12}\,\text{cm/s}
\end{aligned}$$

From Eq. (15) we obtain J_p=4.82 cgse=1.6 × 10^{-5} A/m^2. Let us estimate the critical field E_c in Eq. (10). Assuming η=1.72×10^{-4} g/cm×s, V=0.01 cm/s, R=5×10^{-5} cm, μ=1.5 g/cm^3 and Z=100 we obtain from Eq. (8) E_c=0.015 cgse=450 V/m and σ_0E_c=10 pA/m^2. Figure 2 presents the dependences of vertical electric field on the Earth surface and horizontal electric field in the ionosphere on radial distance calculated from Eqs. (9), (10) and (13) for the external current given by Eq. (14). Spatial distributions of DC electric field in the ionosphere and the vertical electric field on the Earth's surface for the same spatial structure of external current are presented in Fig. 3. These two figures show that at the selected parameters the horizontal electric field in the ionosphere reaches ~10 mV/m, while the vertical electric

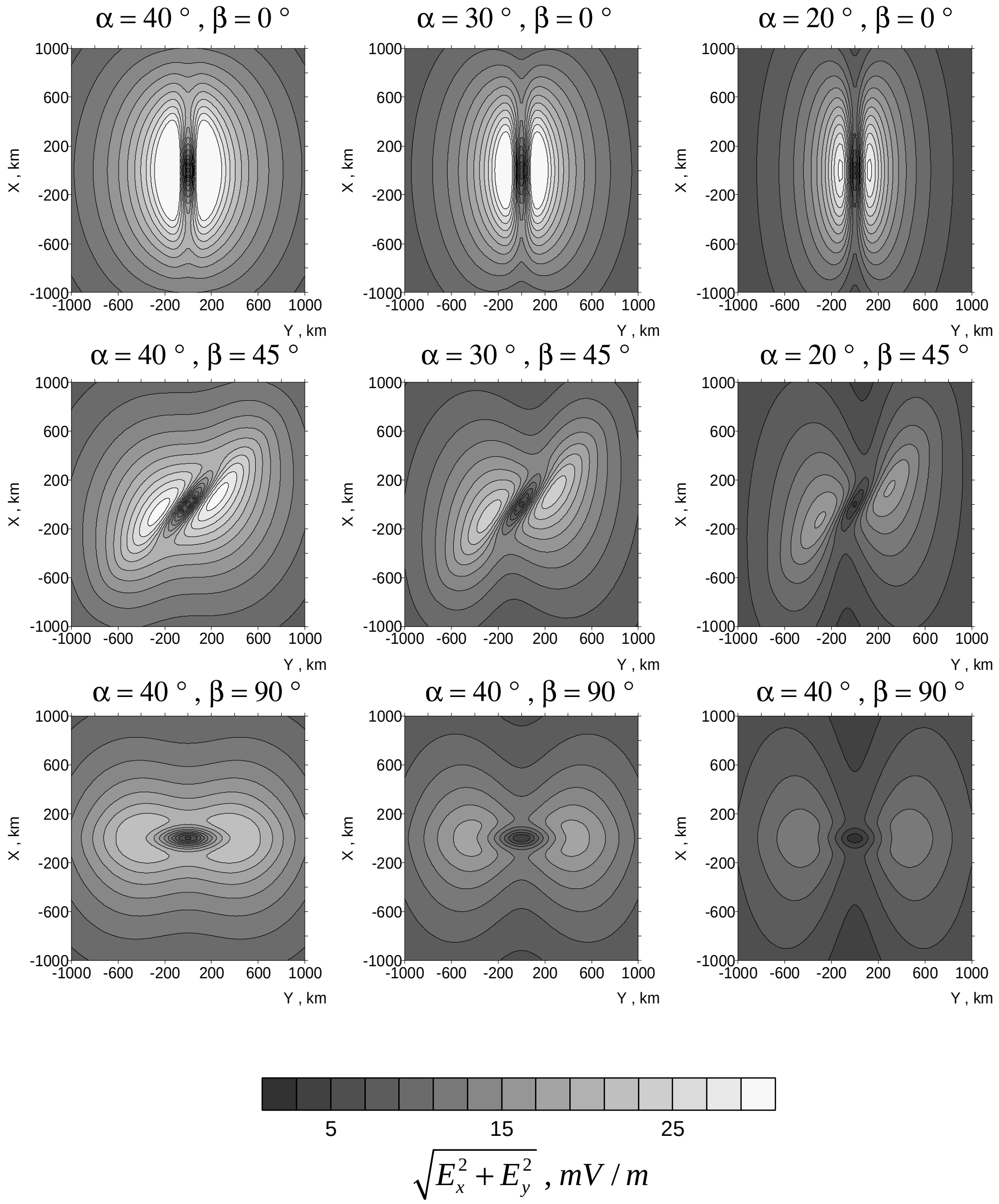

Fig. 4. DC electric field structure in the ionosphere over seismically active fault zone calculated for different angles α of magnetic field inclination and for different angles β of orientation of the fault axis relatively to magnetic meridian plane.

field on the Earth's surface is limited by magnitude ~90 V/m over active fault. Other important result is that DC electric field in the ionosphere has maximal magnitudes at the edges of area of external current. The horizontal scale of vertical electric field enhancement on the ground exceeds the characteristic horizontal scale of external current. Within this area the vertical field practically does not depend on distance. Distributions of the horizontal component of DC electric field in the ionosphere at different angles of magnetic field inclination and orientation of the fault axis relatively to magnetic meridian plane are presented in Fig. 4. Calculations show that the structure of field becomes two-cell (dipole-like). The field component in the plane of meridian strongly depends on the magnetic field inclination.

5 Conclusions

The computation method presented above allows calculating spatial distribution of the conductivity current and related electric field in the ionosphere over active faults for arbitrary altitude dependence of atmospheric conductivity and horizontal distribution of external electric current at oblique geomagnetic field. Convective transport of charged aerosols in the lower atmosphere at different stages of seismic activity development leads to formation of external electric current. Its inclusion in the atmosphere-ionosphere electric circuit is accompanied by amplification of conductivity current flowing into the ionosphere. The current within the conducted layer of the ionosphere is closed in the conjugate ionosphere through the magnetic field-aligned current. It is found that horizontal DC electric field in the ionosphere over seismically active faults can reach the magnitudes up to 10 mV/m and vertical electric field on the Earth surface is limited by the magnitude less then 100 V/m. The ionosphere electric field appeared to be maximal in magnitude at the edges of external current area. The horizontal scale of vertical electric field enhancement on the ground exceeds the characteristic horizontal scale of external current. Within the area of current the vertical field practically does not depend on distance. The field limitation on the Earth surface is caused by feedback mechanism between excited electric field and the causal external current. This feedback is produced by the potential barrier for charged particles at their transfer from ground to the atmosphere. The effect of limitation of the vertical electric field magnitude on the ground creates significant advantage for satellite monitoring of seismic related DC electric field in the ionosphere as compared to ground-based observations. Besides, an amplification of DC electric field in the ionosphere over seismically active faults can be verified by simultaneous measurements of other electromagnetic and plasma effects sensible to growth of DC electric field.

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