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Amplification mechanism of DC electric field in the mid-latitude ionosphere over seismically active faults

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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.

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. Distribution of vertical 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 E = -$\nabla\varphi$ and σ *(z)* denotes atmospheric 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:

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

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:

$$\begin{array}{l} \varphi\,|_{\,z=0} = 0; \quad \sigma_1 \frac{d\varphi}{dz}\Big|_{\,z=z_1-0} = 2\Sigma_P\left(\frac{1}{\sin^2\alpha}\frac{\partial^2\varphi_1}{\partial\,x^2} + \frac{\partial^2\varphi_1}{\partial\,y^2}\right) - \frac{\varphi_1}{\rho}; \\ \rho = \int_0^{z_1}\frac{dz}{\sigma(z)} \end{array}, \qquad (2)$$

where $\varphi_1 = \varphi(x, y, z = z_1)$ is the electric field potential distribution in the ionosphere. This distribution is connected with horizontal component of the electric field and the conductivity current flowing in the ionosphere. Solution of (**??**) satisfying the boundary condition $\varphi|_{z=0} = 0$ has a form:

$$\begin{array}{l} \varphi(x,y,z) = \int\limits_0^z \frac{j_e(x,y,z')}{\sigma(z')}dz' - j_1(x,y)\int\limits_0^z \frac{dz'}{\sigma(z')}; \\ j_1(x,y) = \frac{\varepsilon(x,y)-\varphi_1(x,y)}{\rho}; \quad \varepsilon(x,y) = \int\limits_0^{z_1}\frac{j_e(x,y,z)}{\sigma(z)}dz \end{array} \qquad (3)$$

In this equation $j_1(x, y) = j_1(x, y, z = z_1)$is the conductivity electric current on the lower edge of the ionosphere inflowing from the atmosphere. 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 (**??**) and the boundary condition (**??**) yields approximate equation for electric potential distribution $\varphi_1(x, y)$ in the ionosphere:

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

At $\alpha = \pi/2$ this expression coincides with 2D Poisson equation. Spatial scale of the ionosphere potential distribution in meridian plane depends on the slope of geomagnetic field. Equations (**??**) and (**??**) are applicable for calculation of the electric fields induced by external currents with arbitrary distribution in horizontal plane and for any altitude dependence of the atmosphere electric conductivity in oblique magnetic field. Let us assume that the external electric current over seismic region is formed by superposition of currents arising from the injection of positive and negative charged aerosols into the atmosphere:

$$j_e(x,y,z) = j_p(x,y)s_p(z) - j_n(x,y)s_n(z); \quad s_p(z=0) = s_n(z=0) = 1, \quad (5)$$

Functions $s_p(z),\ s_n(z)$ denote the altitude distributions of external currents. Substitution of (**??**) in (**??**) yields:

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

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 hour. 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 $\sim$ 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. 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. Qualitatively the function characterizing the electric field effect can be presented in a form:

$$j_p = j_{p0}\sqrt{1 + E_{z0}/E_{cp}}; \quad j_n = j_{n0}\sqrt{1 - E_{z0}/E_{cn}},$$

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. Horizontal components of the electric field in the ionosphere

$$E_x(x,y) = -\partial\varphi_1(x,y)/\partial x; \;\; E_y(x,y) = -\partial\varphi_1(x,y)/\partial y$$

at given distribution of the currents $j_{p0}(x,y),\ \ j_{n0}(x,y)$ can be found from the equation:

$$\left(\frac{1}{\sin^2\alpha}\frac{\partial^2}{\partial x^2}+\frac{\partial^2}{\partial y^2}\right)\varphi_1=-\frac{1}{2\rho\Sigma_P}\left[k_p j_{p0}\sqrt{1+\frac{E_{z0}}{E_{cp}}}-k_n j_{n0}\sqrt{1-\frac{E_{z0}}{E_{cn}}}\right]. \tag{6}$$

Vertical electric field in the Earth-ionosphere layer is given by following expression:

$$E_z=\frac{1}{\sigma(z)}\left[\left(\frac{k_p}{\rho}-s_p\right)j_{p0}\sqrt{1+\frac{E_{z0}}{E_{cp}}}-\left(\frac{k_n}{\rho}-s_n\right)j_{n0}\sqrt{1-\frac{E_{z0}}{E_{cn}}}\right]. \tag{7}$$

Equations (**??**) and (**??**) were used for computation of horizontal distribution of the electric field in the ionosphere and on the ground at different inclination of the magnetic field and orientation of the fault axis relatively to magnetic meridian plane.

It is found that horizontal electric field in the ionosphere reaches $\sim$ 10 mV/m and vertical electric field on the Earth surface is limited by magnitude $\sim$ 100 V/m. The ionosphere electric field magnitudes appeared to be maximal 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.