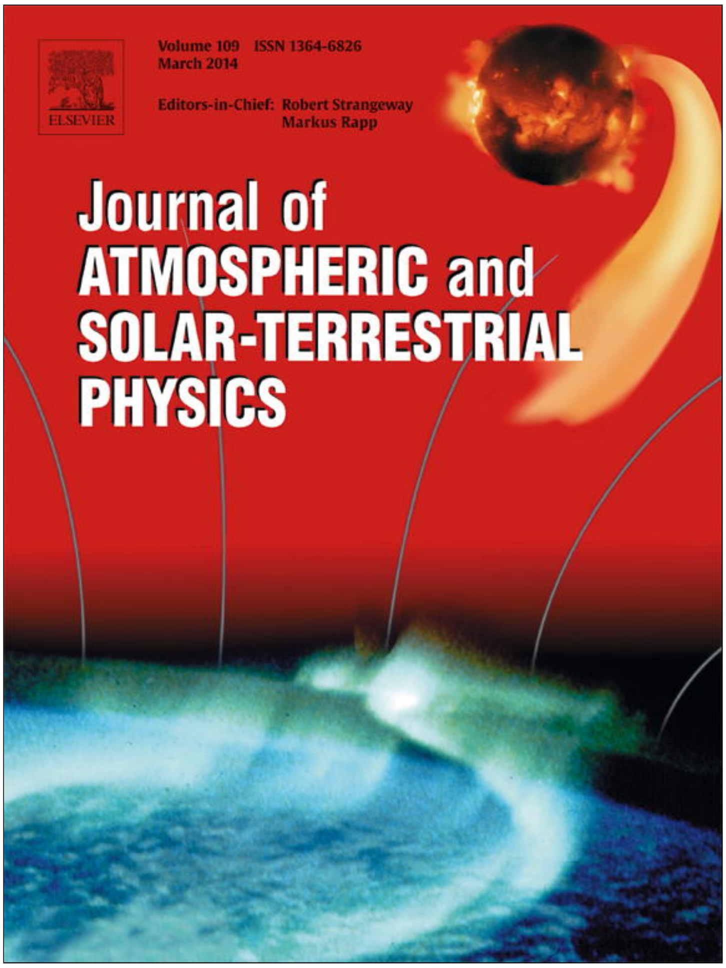
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Scattering of VHF transmitter signals by seismic-related electric discharges in the troposphere

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ABSTRACT

The scattering of VHF electromagnetic waves by random electric discharges occurring in the troposphere over a seismic region has been considered, which are caused by the disturbances of electric current in the global atmosphere–ionosphere circuit. Current disturbances are connected with the injection of charged aerosols as a result of the lifting of soil gases during earthquake preparation. It is shown that the electric field of disturbed current can reach a breakdown value at the altitudes 5–10 km. The method for calculating the mean value of electromagnetic wave fields scattered by the random discharges has been elaborated, which show that the electric field of scattered wave exceeds significantly that of diffracted wave over the horizon. The results of our theory are confirmed by the observational data of VHF transmitter signals over the horizon during earthquake preparation.

1. Introduction

One of perspective studies aimed at earthquake monitoring and prediction is a study of electromagnetic precursors of seismic events. These researches were started by Varotsos and Alexopoulos (1984), Hayakawa and Fujinawa (1994), Gokhberg et al. (1995), Hayakawa (1996), and Nagao et al. (2002). The seismogenic electromagnetic precursors are observed in a wide band of frequencies from quasi-static field up to VHF radio waves. The transmitter signals in different frequency bands are utilized for the electromagnetic sounding of seismic activity (Molchanov and Hayakawa, 2008). Influence of the ionospheric disturbances connected with earthquake preparation on the VLF/LF wave propagation was proved by Gokhberg et al. (1989), Hayakawa et al. (1996), Molchanov and Hayakawa (1998), and Biagi (1999). Moreover, data of observations show that VHF transmitter signals are remarkably increased over the horizon if a seismic region is located close to the propagation path.

The analysis of VHF transmitter signals over the horizon was carried out by Kushida and Kushida (1998, 2002). Significant growth in the signal amplitude is observed if the propagation path is located over the seismic region. Kushida and Kushida (1998, 2002) introduced an empirical earthquake prediction method based on the monitoring of anomalous VHF-band radio waves transmitted from an FM radio station beyond the line of sight. Sakai et al. (2001) showed that anomalous propagation of VHF-band radio waves emitted from a broadcasting station in Sendai City was related to earthquakes with magnitude greater than 5 that occurred in the area between Sendai and the Tateyama observatory in Chiba Prefecture. Fukumoto et al. (2001, 2002) confirmed that the anomalous propagation events were the result of scattering of VHF-band radio waves in the troposphere immediately prior to an earthquake, by documenting reception at an observatory that was beyond the line of sight of transmission location. Pilipenko et al. (2001) showed that the received intensities of scattered waves were stronger when the antenna was at a shallower angle, which implied that the scattering body was in the middle atmosphere rather than in the ionosphere. This conclusion was consistent with the direction finding result by Fukumoto et al. (2001). Fujiwara et al. (2004) also reached the same conclusion. Hayakawa et al. (2007) described a generation mechanism of atmospheric disturbances resulting from changes in geochemical quantities associated with earthquakes and VHF radio wave refraction. Yonaiguchi et al. (2007) discussed that the effect of long-range VHF wave propagation is usually due to the meteorological radio ducting. Moriya et al. (2010) have observed the anomalous VHF-band radio-wave propagation beyond the line of sight prior to earthquakes. Radio waves transmitted from a given FM radio station are considered to be

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scattered in such a way that they could be received by an observation station beyond the line of sight.

The possibility of quasi-static electric field growth up to the breakdown value in the troposphere over the seismic region was shown by Sorokin et al. (2011, 2012a, 2012b). Their calculations show that the area of troposphere with breakdown electric field can be located on the altitude 5–10 km with thickness over several km and with horizontal scale of the order of several hundred km. The growth of electric field is connected with disturbances of electric current in the global electric circuit due to the appearance of electromotive force (EMF) in the lower atmosphere. The EMF caused by the injection of charged aerosols into the atmosphere by soil gases, their convective transport and gravitational sedimentation during an increase in seismic activity (Sorokin et al., 2005, 2007; Sorokin and Hayakawa, 2013). Fig. 1 depicts the example of computation of electric field spatial distribution caused by the injection of charged aerosols into the atmosphere. The region of troposphere with electric field exceeding the breakdown value is marked by hatching. The atmospheric turbulence in this region is excited by the generation of random electric discharges, and the model has been considered by Sorokin et al. (2011, 2012a, 2012b). The same electric discharges are observed in the thunderstorm clouds before lightning, which are called "preliminary breakdown pulse trains" (Clarence and Malan, 1957; Beasley et al., 1982; Proctor et al., 1988; Nag and Rakov, 2008). The models for their generation has been considered by Iudin and Trakhtengerts (2001), Trakhtengerts and Iudin (2005), and Hayakawa et al. (2008).

The occurrence of electric discharges in the troposphere over a seismic region leads to a growth of VHF electromagnetic noise level over the horizon of this region. The theory for the generation of electromagnetic radiation by random discharges in the troposphere was elaborated by Sorokin et al. (2011, 2012a, 2012b), who have calculated the spectrum of electromagnetic radiation on the Earth's surface over the horizon. Their calculation results are confirmed by VHF noise data obtained by Ruzhin et al. (1999, 2000) and Ruzhin and Nomicos (2007) during earthquake

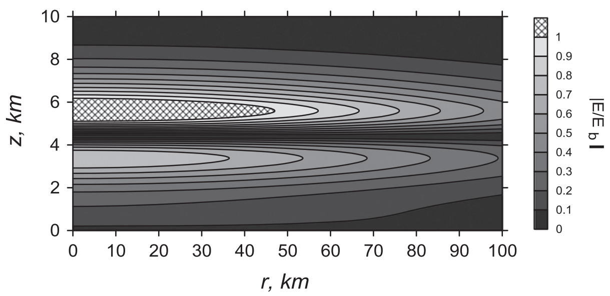


Fig. 1. Calculation result of the spatial distribution of electric field (E) relative to the breakdown value (E_b). The tropospheric region where the electric field attains a breakdown value is indicated by hatching.

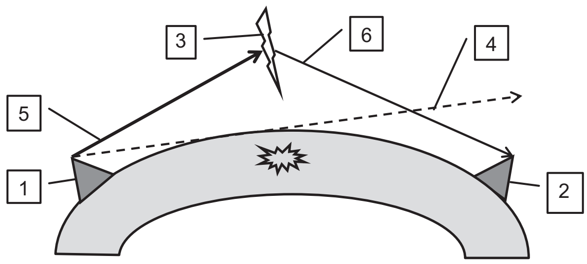


Fig. 2. Scheme of the VHF transmitter signal propagation due to the scattering by the electric discharges. (1) Transmitter. (2) Receiver. (3) Electric discharges in the troposphere. (4) Direction of incident wave propagation. (5) Direction of scattered wave propagation.

preparation. In addition, electric discharges in the troposphere lead to the anomalous VHF transmitter wave propagation. Fig. 2 illustrates the scheme of wave propagation, in which scattering of the VHF transmitter wave by random discharges in the troposphere results in the significant high intensity of scattered wave in comparison with that of diffracted wave. Below we consider the scattering of electromagnetic wave by random discharges and make calculations with special reference to the spatial distribution of electric field mean value in over-the-horizon regions.

2. Electric current generation in conducting discharges by incident electromagnetic wave

We consider the impact of incident VHF transmitter monochromatic wave to the tropospheric region with random electric discharges. Let a discharge be a long and thin vertical conductor with radius a and length $l \gg a$. Transient conductance of the discharge $\sigma(t)$ is assumed to be uniformly distributed along its length. The electric field of the incident wave induces a current of polarization in the discharge. Propagation speed of this current along the discharge is of the order of $\nu \sim 10^7$ m/s. If the discharge has a length $l \sim 10$ m, then the relaxation time of the charge along its length is $l/\nu \sim 10^{-6}$s (Sorokin et al., 2011). This time is much larger than the period of the incident transmitter wave $1/f_0 \sim 10^{-8}$s, so that the electric current induced by the incident wave in the discharge is considered to be quasi-static. We use the long line approximation to calculate the electric current induced by the incident monochromatic wave in the conducting discharges with limited length. This approximation is widely used for the computation of the spatial – temporal characteristics of lightning discharges. Fig. 3 depicts our Cartesian coordinate system x, y, z with z axis directed upward, and the origin of coordinates is located on the Earth's surface. The source of radiation is a vertical electric dipole located at the origin of coordinates. The random electric discharges are generated in the region of troposphere, in which the electric field attains a breakdown value. The center of conducting discharge with number k is determined by its radius–vector $\mathbf{r}_k$ as depicted in Fig. 3. Let the electric field vertical component of incident wave with frequency ω_0 at the distance $\mathbf{r}_k$ to be expressed as $E_0(\mathbf{r}_k)\exp(-i\omega_0 t)$. The potential of discharge surface V and the induced electric current I in the transmission line approximation (Sadiku, 2007) are defined as follows:

$$-\frac{\partial V}{\partial z} - b\frac{\partial I}{\partial t} = E_s + E_0(\mathbf{r}_k)\exp(-i\omega_0 t); \quad C\frac{\partial V}{\partial t} + \frac{\partial I}{\partial z} = 0;$$
$$C \approx \frac{2\pi\varepsilon_0}{\log(l/a)}; \quad b \approx \frac{\mu_0}{2\pi}\log(l/a) = \varepsilon_0\mu_0/C \quad (1)$$

where E_s is the longitudinal component of electric field on the discharge surface, C is the discharge capacitor per unit length, b is the discharge inductance per unit length, ε_0 is the electric constant of

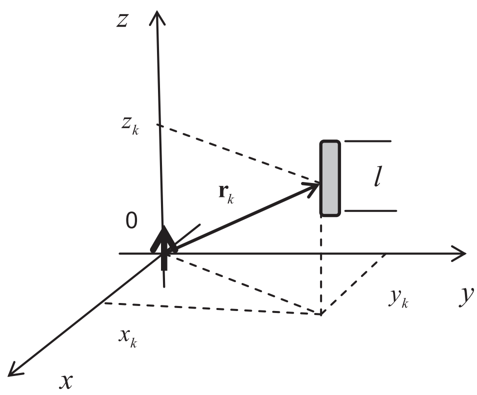


Fig. 3. The coordinates used for the calculation.

free space, μ_0 is the permeability of free space, and c is the light speed. The current is equal to zero at the ends of the discharge

$$I(z_k+l/2,t)=I(z_k-l/2,t)=0 \quad (2)$$

Discharge conductivity σ is slowly varying in comparison with the period $2\pi/\omega_0$ of the incident wave. In this case all quantities are dependent on time as a harmonic function $\exp(-i\omega_0 t)$, and the electric field $E_s(z,t)$ on the discharge surface is connected with the current $I(z,t)$ on the discharge by the following equation:

$$E_s(z,t)=R(\omega_0,t)I(z,t). \quad (3)$$

In Eq. (3) the discharge resistance per unit length $R(\omega_0,t)$ is defined by the following formula (Landau et al., 1984):

$$R(\omega_0,t)=\frac{(1+i)\sqrt{\mu_0\sigma(t)\omega_0/2}}{2\pi\sigma(t)a}\frac{J_0((1+i)a\sqrt{\mu_0\sigma(t)\omega_0/2})}{J_1((1+i)a\sqrt{\mu_0\sigma(t)\omega_0/2})}, \quad (4)$$

where $J_{0,1}$ is the Bessel functions of zero and first order. Let the potential and current be a product of a slowly changing function and a fastly changing exponential function as follows:

$$I(z,t)=I_0(z,t)\exp(-i\omega_0 t)$$
$$V(z,t)=V_0(z,t)\exp(-i\omega_0 t). \quad (5)$$

Substituting Eqs. (5) and (3) in Eq.(1) and excluding V_0, one obtains the equation to determine the function I_0

$$\frac{d^2 I_0}{dz^2}+q^2(t)I_0=i\omega_0\, CE_0.$$

The solution of this equation with the boundary condition (2) has a form

$$I(\mathbf{r}_k,z-z_k,t)=I_0(\mathbf{r}_k,z-z_k,t)\exp(-i\omega_0 t)$$
$$I_0(\mathbf{r}_k,z-z_k,t)=\frac{i\omega_0 Cl^2 E_0(\mathbf{r}_k)}{[q(t)\,l]^2}\left\{1-\frac{\cos\,[q(t)\,(z-z_k)]}{\cos\,[q(t)\,(l/2)]}\right\}.$$
$$q^2=k_0^2+i\omega_0 CR(\omega_0,t);\quad k_0=\omega_0/c \quad (6)$$

Eq. (6) allows us to compute spatial–temporal distributions of electric current induced by the incident wave in the discharges, and this current form a source of scattering radiation of the incident wave.

3. Electromagnetic radiation scattered by the electric discharges

The source of scattering radiation is an electric current induced by the incident wave in the discharges. This current occurs in the random points and at the random moments of time in the tropospheric region in which the electric field attains the breakdown value. Let the discharged region of atmosphere be as cells with numbers k. Each center of the cell is located at the points with radius–vector $\mathbf{r}_k$ as depicted in Fig. 4. Spatial scale of a cell is of the order of spatial scale of the discharge, and each of discharges occurs in one of cells. The time moments of discharge form a sequence of random values in each cell as $t_{k\alpha}=t_{k1},t_{k2},\ldots$. We designate the spatial–temporal distribution of induced current density in each discharge as $\mathbf{j}_{k\alpha}=\mathbf{j}_{k\alpha}(\mathbf{r}_k,t-t_{k\alpha})$. The current density of mirror image of the discharge in the perfectly conducting surface of the Earth $z=0$ is designated by $\mathbf{j}^*_{k\alpha}=\mathbf{j}^*_{k\alpha}(\mathbf{r}^*_k,t-t_{k\alpha})$. The positions of the discharge and its mirror image are presented in Fig. 4, in which the radius–vector $\mathbf{r}_k$ has the components (x_k,y_k,z_k), and the corresponding radius–vector $\mathbf{r}^*_k$ has the components $(x_k,y_k,-z_k)$. Electric field strength $\mathbf{E}_{k\alpha}$ and magnetic field strength $\mathbf{H}_{k\alpha}$ of the radiation are defined by Maxwell equations

$$\nabla\times\mathbf{H}_{k\alpha}=\mathbf{j}_{k\alpha}+\mathbf{j}^*_{k\alpha}+\varepsilon_0\frac{\partial\mathbf{E}_{k\alpha}}{\partial t};\quad \nabla\times\,\mathbf{E}_{k\alpha}=-\mu_0\frac{\partial\mathbf{H}_{k\alpha}}{\partial t}$$
$$\nabla\cdot\mathbf{E}_{k\alpha}=\frac{\rho+\rho^*}{\varepsilon_0};\quad \nabla\cdot\mathbf{H}_{k\alpha}=0.$$

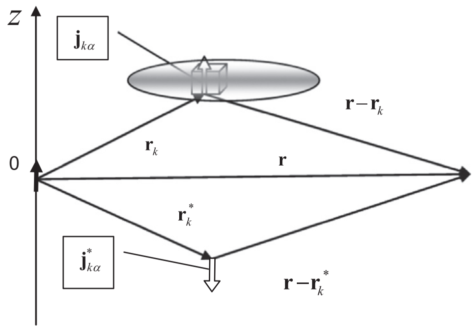


Fig. 4. Scheme of the location of induced current in the discharge and its image in the perfectly conducting Earth.

where ρ and ρ^* are the charge densities in the discharge and in its mirror image correspondingly. Electromagnetic field radiated by the tropospheric region with random discharges is defined by the following equations

$$\mathbf{E}=\sum_{k\alpha}\mathbf{E}_{k\alpha};\quad \mathbf{H}=\sum_{k\alpha}\mathbf{H}_{k\alpha} \quad (7)$$

We consider scattered electromagnetic field on the Earth's surface. The radius–vector of the observation point $\mathbf{r}$ is situated in the plane $(x,\,y)$. In Fraunhofer zone $|\mathbf{r}-\mathbf{r}_k|\gg l^2/\lambda\sim l^2\omega_0/c$ the field of discharge radiation is defined by a vector potential $\mathbf{A}_{k\alpha}$ by using the following formulas:

$$\mathbf{E}_{k\alpha}=\left(\frac{\partial\mathbf{A}_{k\alpha}}{\partial t}\times\mathbf{n}_k\right)\times\mathbf{n}_k+\left(\frac{\partial\mathbf{A}^*_{k\alpha}}{\partial t}\times\mathbf{n}^*_k\right)\times\mathbf{n}^*_k;$$
$$\mathbf{H}_{k\alpha}=\frac{1}{Z_0}\left(\frac{\partial\mathbf{A}_{k\alpha}}{\partial t}\times\mathbf{n}_k\right)+\frac{1}{Z_0}\left(\frac{\partial\mathbf{A}^*_{k\alpha}}{\partial t}\times\mathbf{n}^*_k\right); \quad (8)$$
$$Z_0=\sqrt{\mu_0/\varepsilon_0};\quad \mathbf{n}_k=(\mathbf{r}-\mathbf{r}_k)/|\mathbf{r}-\mathbf{r}_k|;\quad \mathbf{n}^*_k=(\mathbf{r}-\mathbf{r}^*_k)/|\mathbf{r}-\mathbf{r}^*_k|.$$

The vector potentials of scattered radiation $\mathbf{A}_{k\alpha}$, $\mathbf{A}^*_{k\alpha}$ are defined by the density of radiating currents according to the following approximation formula:

$$\mathbf{A}_{k\alpha}(\mathbf{r},t)=\frac{\mu_0}{4\pi|\mathbf{r}-\mathbf{r}_k|}\int\mathbf{j}_{k\alpha}\left(\mathbf{r}',t-t_{k\alpha}-\frac{|\mathbf{r}-\mathbf{r}_k|}{c}+\frac{\mathbf{n}_k\cdot\mathbf{r}'}{c}\right)d\mathbf{r}';$$
$$\mathbf{A}^*_{k\alpha}(\mathbf{r},t)=\frac{\mu_0}{4\pi|\mathbf{r}-\mathbf{r}^*_k|}\int\mathbf{j}^*_{k\alpha}\left(\mathbf{r}',t-t_{k\alpha}-\frac{|\mathbf{r}-\mathbf{r}^*_k|}{c}+\frac{\mathbf{n}^*_k\cdot\mathbf{r}'}{c}\right)d\mathbf{r}' \quad (9)$$

Integration is performed over the volume of radiating current in Eq. (9). As the induced current flows in the thin vertical conductor with length l the vector of current density has vertical component $j_{k\alpha}$. The spatial – temporal distribution of current density in the discharges is considered to have the following form:

$$j_{k\alpha}=I(x_k,y_k,z-z_k,t-t_{k\,\alpha})\delta(x-x_k)\delta(y-y_k)$$
$$j^*_{k\alpha}=I(x_k,y_k,z+z_k,t-t_{k\,\alpha})\delta(x-x_k)\delta(y-y_k). \quad (10)$$

The horizontal component of electric field tends to zero and the vertical component of magnetic field is doubled on the perfectly conducting Earth's surface. Substituting Eqs. (8) and (9) in Eq. (7) and using the spatial–temporal distribution of vertical component of the radiating current Eq. (10) one obtains the formulas for the component of electromagnetic field.

$$E_z(\mathbf{r},t)=-\frac{\mu_0}{2\pi}\sum_{k,\alpha}\frac{1-n^2_{kz}}{|\mathbf{r}-\mathbf{r}_k|}\frac{\partial}{\partial t}\int_{-l/2}^{l/2}d\xi I\left(\mathbf{r}_k,\xi,t-t_{k\alpha}-\frac{|\mathbf{r}-\mathbf{r}_k|}{c}+\frac{n_{kz}\xi}{c}\right);$$
$$\mathbf{H}_\perp(\mathbf{r},t)=\frac{\mu_0}{4\pi Z_0}\sum_{k,\alpha}\frac{(\mathbf{e}_z\times\mathbf{n}_{k\perp})}{|\mathbf{r}-\mathbf{r}_k|}\frac{\partial}{\partial t}\int_{-l/2}^{l/2}d\xi I\left(\mathbf{r}_k,\xi,t-t_{k\alpha}-\frac{|\mathbf{r}-\mathbf{r}_k|}{c}+\frac{n_{kz}\xi}{c}\right). \quad (11)$$

The integration in Eq. (11) is performed on the length of the conducting discharge $z-z_k=\xi$, and the electromagnetic field in Eq. (11) is the total radiation generated by the induced current in all discharges of all cells. The spatial distribution of radiation components on the Earth's surface occurring by the scattering of incident wave by the random discharges in the troposphere are defined by the following equations:

$$E_z(\mathbf{r}) = k_0^2 L^3 \left\{ \int_V d\mathbf{r}' N(\mathbf{r}') E_0^2(\mathbf{r}') \frac{(1-n_z^2)^2}{|\mathbf{r}-\mathbf{r}'|^2} \int_{-\infty}^{\infty} \frac{d\omega}{2\pi} |\tilde{\Phi}(\omega-\omega_0, n_z)|^2 \right\}^{1/2};$$

$$\mathbf{H}_\perp(\mathbf{r}) = \frac{k_0^2 L^3}{Z_0} \left\{ \int_V d\mathbf{r}' N(\mathbf{r}') E_0^2(\mathbf{r}') \frac{(\mathbf{e}_z \times \mathbf{n}_{k\perp})}{|\mathbf{r}-\mathbf{r}'|^2} \int_{-\infty}^{\infty} \frac{d\omega}{2\pi} |\tilde{\Phi}(\omega-\omega_0, n_z)|^2 \right\}^{1/2}. \tag{12}$$

These equations have been obtained in Appendix (Formulas (A8) and (A9)). In Eq. (12) the integration is done over the volume of troposphere in which the electric field of disturbed current of global circuit attains a breakdown value. Using the Parseval equality (Titchmarsh, 1986)

$$\int_{-\infty}^{\infty} |\tilde{\Phi}(\omega, n_z)|^2 \, d\omega = 2\pi \int_{-\infty}^{\infty} |\Phi(t, n_z)|^2 \, dt,$$

we rewrite Eq. (12) as follows:

$$E_z(\mathbf{r}) = k_0^2 L^3 \left\{ \int_V d\,\mathbf{r}' N(\mathbf{r}') E_0^2(\mathbf{r}') G(\mathbf{r}-\mathbf{r}') \right\}^{1/2} \tag{13}$$

The Green function in Eq. (13) is defined by the following formula:

$$G(\mathbf{r}-\mathbf{r}') = \frac{(1-n_z^2)^2}{|\mathbf{r}-\mathbf{r}'|^2} \int_{-\infty}^{\infty} |\Phi(t, n_z)|^2 \, dt. \tag{14}$$

$$\Phi(t, n_z) = \frac{\cos(k_0 n_z l/2)}{(ql)[(k_0 n_z l)^2 - (ql)^2]} \left[\tan\left(\frac{ql}{2}\right) - \frac{q}{k_0 n_z} \tan\left(\frac{k_0 n_z l}{2}\right) \right]. \tag{15}$$

Eqs. (13)–(15) allow us to calculate the spatial distribution of electric field (mean value) of the scattered radiation on the Earth's surface. Under the sign of integration in Eq. (13) there are given the electric field of incident wave $E_0(\mathbf{r})$ and the spatial distribution of discharges frequency in a unit volume.

4. Calculation of scattered electromagnetic radiation

We calculate the spatial distribution of electromagnetic field on the Earth's surface. The discharges are spread in a region of troposphere where the electric field attains the breakdown value. This region is situated in the vicinity of a propagation path of VHF transmitter signal as is depicted in Fig. 2, and Eq. (13) is used to compute it. According to the graph in Fig. 1 the horizontal scale of disturbed region can be hundreds km, while its thickness is only over several km. Consequently, the spatial distribution of volume density of frequency of discharges in Eq. (13) can be expressed in the form

$$N(x, y, z) = N_0(x, y)\delta(z - z_0), \tag{16}$$

where $\delta(z)$ is the delta function, z_0 is the altitude of a thin tropospheric layer with discharges, and $N_0(x, y)$ is the surface density of frequency of discharges. Substituting Eq. (16) in Eq. (13) and integrating Eq. (13) over z, leads to

$$E_z(\mathbf{r}) = k_0^2 L^3 \left[\iint N_0(x', y') E_0^2(x', y', z_0) G(x-x', y-y') dx' dy' \right]^{1/2}$$

$$G(x, y) = \left(\frac{1-n_z^2}{R} \right)^2 \int_{-\infty}^{\infty} |\Phi(t, n_z)|^2 \, dt; \quad R^2 = x^2 + y^2 + z_0^2, \quad n_z = -z_0/R. \tag{17}$$

In Eq. (17) the integration is done over the surface of disturbed region, and the function $\Phi(t, n_z)$ is defined by Eq. (15).

The spatial distribution of density of discharges frequency in the tropospheric region where the electric field attains the breakdown value is given by,

$$N(x, y, z) = N_m \eta[d(x, y) - |z - z_0|]$$

where N_m is the density of discharges in the center of the disturbed region, and $\eta(x)$ is the Heaviside step function. According to Fig. 1 the dependence of half-thickness of disturbed region $d(x, y)$ on the horizontal coordinates is assumed as follows:

$$d(x, y) = d_0 \left[1 - \frac{(x - x_s)^2}{r_x^2} - \frac{(y - y_s)^2}{r_y^2} \right], \tag{18}$$

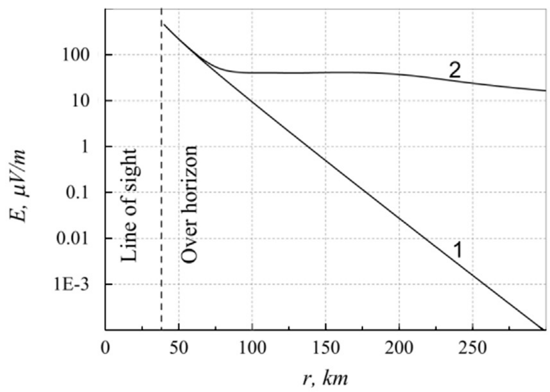
where (x_s, y_s) is the coordinates of disturbed region epicenter, d_0 is the half-thickness of disturbed region in its epicenter, and $2r_{x,y}$ is the scales of disturbed region along x, y axes. From Eq. (16) we yield

$$N_0(x, y) = \int_{z_0 - d(x,y)}^{z_0 + d(x,y)} N(x, y, z) \; dz = 2N_m d(x, y). \tag{19}$$

We consider that the transmitter is located at the altitude h_1 and the receiver is located at the altitude h_2. In Eq. (17) the spatial distribution of transmitter electromagnetic wave $E_0(x, y, z_0)$ on the plane $z = z_0$ has a form

$$E_0(x, y) = \frac{U_0}{\sqrt{x^2 + y^2 + z_0^2}} \left[1 - \frac{z_0^2}{x^2 + y^2 + z_0^2} \right], \tag{20}$$

where $U_0 = \sqrt{3Z_i W / 2\pi}$, $Z_i = 377$ Ohm, and W is the transmitter power. Eqs. (17)–(20) are used to compute the spatial distribution of electric field (mean value) on the Earth's surface. We have calculated the electric field E_d of diffracted wave of transmitter



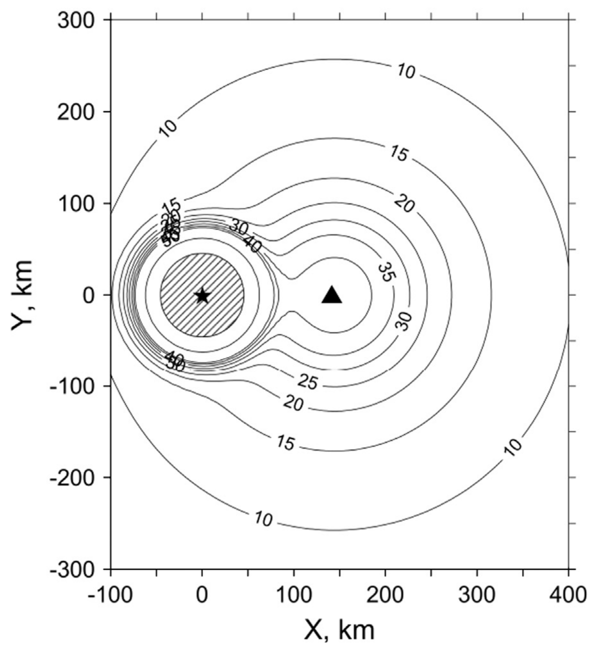


Fig. 5. Calculation result of the spatial distribution of VHF transmitter electric field propagating over the horizon due to their scattering by electric discharges in the axial symmetric tropospheric region $r_x = r_y = 50$ km.

radiation over the horizon and the electric field E of wave scattered by random discharges in the troposphere. Electric field E_d was calculated by formulas cited in Fock (1965), and the mean value of the scattering field E was calculated by Eqs. (17)–(20). According to the statistical independence of E_d and E, the mean value of total electric field E_t over the horizon was calculated by the following formula:

$$E_t = \sqrt{E_d^2 + E^2}. \tag{21}$$

Figs. 5 and 6 depict the calculation results of spatial distribution of wave electric field. The dependence of field amplitude on distance has been calculated along the line passed through the point of transmitter and the epicenter of seismic region (upper graphs). Curve 1 is the amplitude of transmitter electric field E_d propagated by diffraction around the spherical Earth. Curve 2 is the mean value of total electric field E_t. Bottom graphs of Figs. 5 and 6 illustrate the calculation results of horizontal distribution of total electric field (mean value). An asterisk denotes the location of the transmitter and triangles denote the epicenter of seismic region. The geometric line-of-site region is marked by hatching. The radius of this region R_v is defined by the formula (Kerr, 1988)

$$R_v = \sqrt{2R_g}(\sqrt{h_1} + \sqrt{h_2}),$$

where R_g is the Earth's radius. In the calculations we have used the following values: $h_1 = 30$ m, $h_2 = 30$ m, $R_v \approx 40$ km, $W = 5$ kW, $U_0 = 950$ V. The distance from the transmitter to the earthquake epicenter is 150 km, and the frequency of transmitter radiation is $f_0 = \omega_0 / 2\pi = 80$ MHz. The conductivity of discharge depends on time as follows.

$$\sigma(t) = \sigma_0 \exp(-t/t_0)\eta(t).$$

Let us choose the following parameters in the calculation of the current induced in the discharges: $l = 10$m, $a = 5 \times 10^{-3}$m, $\sigma_0 = 2 \times 10^{-3} S/m$, $t_0 = 4 \times 10^{-3}$s. Our calculations show that the field amplitude of scattered wave exceeds significantly that of diffracted wave over the horizon.

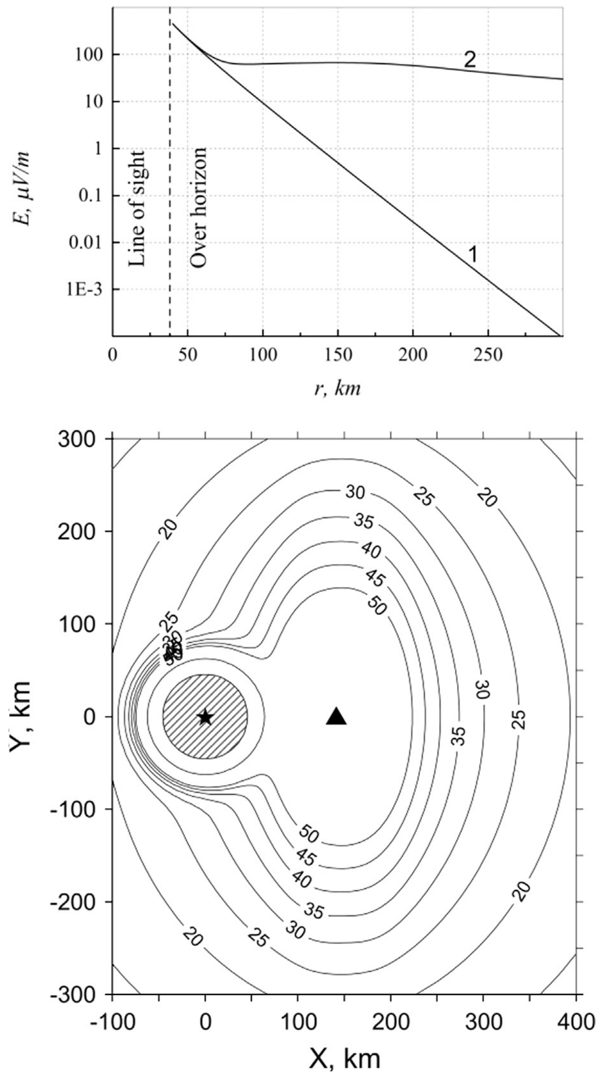


Fig. 6. Calculation result of the spatial distribution of VHF transmitter electric field propagating over the horizon due to their scattering by electric discharges in the elliptical tropospheric region $r_x = 500$ km; and $r_y = 300$ km.

5. Conclusion

Registration of the VHF transmitter signals over the horizon shows that their amplitude increases significantly during earthquake preparation if the epicenter of a coming earthquake is located in the vicinity of signal propagation path. The result of observations indicates that the troposphere region influences the signal propagation over a seismic zone. That is, the anomaly in signal propagation is observed during several days before an earthquake. Growth of the quasi-static electric field value up to 10 mV/m in the ionosphere is observed in the same period, and such a field in the ionosphere appeared by any disturbance of electric current in the atmosphere–ionosphere global circuit. The source of current disturbances is an electromotive force occurring by an increase in emanation of soil gases and the injection of charged aerosols in the atmosphere during the growth of seismicity. Our calculations show that the electric field of conducting current in the atmosphere–ionosphere circuit can attain a breakdown value in the troposphere at the altitudes 5–10 km. Atmosphere turbulence at these altitudes results in the random electric discharges formation. The signal of VHF transmitter is scattered by the discharges because they have a significant electric conductivity. It is shown that the signals of VHF transmitter are scattered in the level of troposphere with random discharges which are located at the altitudes from 5 up to 10 km. The thickness of this level is of the order of few km. The scattered field is propagated over the horizon with respect to the transmitter. The scattered wave is found to exhibit spectral line broadening $\Delta f_0 \sim 1/t_0$ if the transmitter wave is monochromatic. The line broadening of scattered wave is connected with the temporal dependence of discharge conductivity and it can have a value of the order of 0.1–1 kHz. The observed anomaly in the signal propagation of VHF transmitter at the eve of an earthquake is explained by the generation of scattered field over the horizon. Based on our elaborated theory the spatial distribution of mean value of scattered wave electric field over the horizon has been calculated. These results of calculations are confirmed by the reports of observation of VHF transmitter signals over the horizon propagation during earthquake preparation.

Appendix

Let us estimate the spatial distribution of electromagnetic radiation of the induced current in the conducting discharges in each cell at the moment of time $t_{k\alpha}$. The electromagnetic components of scattered field are defined by Eq. (11).

$$E_z(\mathbf{r},t) = -\frac{\mu_0}{2\pi}\sum_{k,\alpha}\frac{1-n_{kz}^2}{|\mathbf{r}-\mathbf{r}_k|}\frac{\partial}{\partial t}\int_{-l/2}^{l/2} d\xi I\left(\mathbf{r}_k,\xi,t-t_{k\alpha}-\frac{|\mathbf{r}-\mathbf{r}_k|}{c}+\frac{n_{kz}\xi}{c}\right);$$
$$\mathbf{H}_\perp(\mathbf{r},t) = \frac{\mu_0}{4\pi Z_0}\sum_{k,\alpha}\frac{(\mathbf{e}_z\times\mathbf{n}_{k\perp})}{|\mathbf{r}-\mathbf{r}_k|}\frac{\partial}{\partial t}\int_{-l/2}^{l/2} d\xi I\left(\mathbf{r}_k,\xi,t-t_{k\alpha}-\frac{|\mathbf{r}-\mathbf{r}_k|}{c}+\frac{n_{kz}\xi}{c}\right).$$

From these equations the vertical component of electric field can be written in a general form.

$$E_z(\mathbf{r},t) = \sum_{k,\alpha} f_k(t-t_{k\alpha})$$
$$f_k(t) = -\frac{\mu_0}{2\pi}\frac{(1-n_{kz}^2)}{|\mathbf{r}-\mathbf{r}_k|}\frac{\partial}{\partial t}\int_{-l/2}^{l/2} d\xi I\left(\mathbf{r}_k,\xi,t-\frac{|\mathbf{r}-\mathbf{r}_k|}{c}+\frac{n_{kz}\xi}{c}\right). \quad (A1)$$

Horizontal components of magnetic field have the same form, so that we will consider only the component of electric field below. For the definition of statistical characteristics of random process we believe that for each cell with number k in the moments of time $t_{k\alpha} = \{t_{k1}, t_{k2}\ldots\}$ it is formed as independent sequences with frequency ν_k which is defined by the formula $\sum f_k(t-t_{k\alpha}) = \nu_k f_k(t)$. Taking into account that random quantities in the cell with different number k are statistical independent in (A1), one finds (Yaglom, 1987),

$$\langle E_z(\mathbf{r},t)\rangle = \sum_k \nu_k \int_{-\infty}^{\infty} f_k(t)dt = 0$$
$$P_z^{(E)}(\mathbf{r},t) = \langle E_z(\mathbf{r},t+\tau)E_z(\mathbf{r},\tau)\rangle = \sum_k \nu_k \int_{-\infty}^{\infty} f_k(\tau+t)f_k(\tau)d\tau \quad (A2)$$

The spatial distribution of mean value of electric field component $E_z(\mathbf{r})$ scattered by random discharges is defined as follows:

$$E_z(\mathbf{r}) = \sqrt{\frac{1}{2\pi}\int_{-\infty}^{\infty} P_z^{(E)}(\mathbf{r},\omega)d\omega}, \quad (A3)$$

where $P_z^{(E)}(\mathbf{r},\omega)$ is the Fourier component of the function $P_z^{(E)}(\mathbf{r},t)$. One finds from (A2),

$$P_z^{(E)}(\mathbf{r},\omega) = \int_{-\infty}^{\infty} dt\exp(i\omega t)P_z^{(E)}(\mathbf{r},t) = \sum_k \nu_k|\tilde{f}_k(\omega)|^2$$
$$\tilde{f}_k(\omega) = \frac{i\omega\,\mu_0}{2\pi}\frac{1-n_{kz}^2}{|\mathbf{r}-\mathbf{r}_k|}\exp\left(i\omega\frac{|\mathbf{r}-\mathbf{r}_k|}{c}\right)\int_{-\infty}^{\infty} dt\exp[i(\omega-\omega_0)t]$$
$$\int_{-l/2}^{l/2} d\xi I_0(\mathbf{r}_k,\xi,t)\exp\left(-i\omega\frac{n_{kz}\xi}{c}\right). \quad (A4)$$

In the second equation of (A4) integration is performed over the length of a conducting discharge. We use Eq. (6) to compute this integral, and the results are as follows.

$$\int_{-l/2}^{l/2} I_0(\mathbf{r}_k,\xi,t)\exp\left(-i\omega\frac{n_{kz}\xi}{c}\right)d\xi = 2i\omega\,{}_0Cl^2E_0(\mathbf{r}_k)\Phi(t,n_{kz})$$
$$\Phi(t,n_{kz}) = \frac{\cos(k_0n_{kz}l/2)}{(ql)[(k_0n_{kz}l)^2-(ql)^2]}\left[\tan\left(\frac{ql}{2}\right)-\frac{q}{k_0n_{kz}}\tan\left(\frac{k_0n_{kz}l}{2}\right)\right]. \quad (A5)$$

Substitution of Eq. (A5) in (A4) allows us to rewrite the formula (A4) in the form.

$$P_z^{(E)}(\mathbf{r},\omega) = (kk_0L^3)^2\sum_k \nu_k E_0^2(\mathbf{r}_k)\frac{(1-n_{zk})^2}{|\mathbf{r}-\mathbf{r}_k|^2}|\tilde{\Phi}(\omega-\omega_0,n_{zk})|^2;$$
$$\tilde{\Phi}(\omega-\omega_0,n_{zk}) = \int_{-\infty}^{\infty}\Phi(t,n_{zk})\exp[i(\omega-\omega_0)t]dt;$$
$$k=\omega/c; \quad L = l(2/\log(l/a))^{1/3}. \quad (A6)$$

Let us define the volume density of frequency of discharges $N(\mathbf{r}_k)$ in the cell with number k by the formula $\nu_k = N(\mathbf{r}_k)\Delta V_k$ where ΔV_k is the volume cell with number k. Substituting this in Eq. (A6), summation over k in the integration over the volume V region, and involving discharges based on the formula $\sum_k \nu_k F(\mathbf{r}_k) = \int_V N(\mathbf{r}') F(\mathbf{r}')d\mathbf{r}'$, one finds,

$$P_z^{(E)}(\mathbf{r},\omega) = (kk_0L^3)^2\int_V N(\mathbf{r}')E_0^2(\mathbf{r}')\frac{(1-n_z^2)^2}{|\mathbf{r}-\mathbf{r}'|^2}|\tilde{\Phi}(\omega-\omega_0,n_z)|^2 d\,\mathbf{r}'. \quad (A7)$$

Substituting Eq. (A7) in (A3), we find the spatial distribution on the Earth's surface of the component of electric field radiation scattered by random discharges

$$E_z(\mathbf{r}) = k_0^2L^3\left\{\int_V d\,\mathbf{r}'N(\mathbf{r}')E_0^2(\mathbf{r}')\frac{(1-n_z^2)^2}{|\mathbf{r}-\mathbf{r}'|^2}\int_{-\infty}^{\infty}\frac{d\omega}{2\pi}|\tilde{\Phi}(\omega-\omega_0,n_z)|^2\right\}^{1/2}. \quad (A8)$$

In Eq. (A8) we accept $k\approx k_0$, because the function (A7) is non-trivial only in the vicinity of a point $\omega=\omega_0$. The same way of calculation leads to the spatial distribution of components of magnetic field radiation scattered by random discharges

$$\mathbf{H}_\perp(\mathbf{r}) = \frac{k_0^2L^3}{Z_0}\left\{\int_V d\,\mathbf{r}'N(\mathbf{r}')E_0^2(\mathbf{r}')\frac{(\mathbf{e}_z\times\mathbf{n}_{k\perp})}{|\mathbf{r}-\mathbf{r}'|^2}\int_{-\infty}^{\infty}\frac{d\omega}{2\pi}|\tilde{\Phi}(\omega-\omega_0,n_z)|^2\right\}^{1/2}. \quad (A9)$$

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