Journal of Applied Mechanics and Technical Physics, Vol. 39, No. 6, 1998

RADIATION MECHANISM OF GENERATION OF GEOMAGNETIC SIGNALS FROM UNDERGROUND AND CONTACT EXPLOSIONS

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UDC 550.388.2

A mechanism is proposed for the generation of geomagnetic perturbations by an atmospheric electrical dipole formed by the gamma radiation from contact and underground explosions accompanied by formation of a ground dome and escape of explosion products into the atmosphere. The gyrotropic E-layer of the ionosphere plays a determining role in the generation of geomagnetic fluctuations at long epicentral distances. The amplitude-frequency parameters of a geomagnetic signal at 1000 km from a contact explosion with an energy of 150 ktons are estimated. The possibility of recording such geomagnetic signals from explosions with emission of gamma radiation into the atmosphere is shown.

It has been experimentally established that underground and contact explosions are accompanied by generation of geomagnetic and geoelectric perturbations of frequency in the range from 10^{-3} to 10 Hz [1–3]. Different mechanisms for the perturbation generation have been considered with a detailed calculation of perturbation parameters [1–6]. In [1–4], the electromagnetic-field components on the Earth's surface produced by equivalent electrical and magnetic dipoles in the case of a deep underground explosion were calculated. In contact and underground explosions accompanied by formation of a ground dome and radioactive emissions into the atmosphere, the processes of separation and relaxation of electric charges result in generation of a low-frequency electric field in the terrestrial atmosphere [2, 3]. The interaction of ionized products of an underground explosion with the geomagnetic field leads to generation of magnetic perturbations [5]. The shock and the seismic waves produced by the underground explosion generate currents that distort the geomagnetic field [6]. A common feature of the studies cited was that the parameters of geomagnetic and geoelectric signals were calculated in a near zone of explosions at epicentral distances not exceeding several kilometers. At the same time, the detection of underground and contact explosions at epicentral distances longer than 100 km is of practical interest today [7]. The detection and identification of underground explosions in cavities filled with air (tests with decoupling) [8, 9] is also an important problem. Recording of seismic waves produced by such explosions against the background of a great many seismic events involves considerable difficulties, which can be overcome by using modern methods of detection and identification of underground and contact explosions, in particular, the method of recording geomagnetic and geoelectric perturbations. The goal of the present work is to estimate the parameters of geomagnetic perturbations from underground and contact explosions at long epicentral distances.

The E-layer of the ionosphere plays a determining role in the formation of geomagnetic perturbations from underground and contact explosions at epicentral distances exceeding 100 km. In recent years, another mechanism for the generation of geomagnetic perturbations has been the subject of considerable discussion (see, for example, [10]): underground explosions produce air waves, which propagate vertically upward and, reaching the lower boundary of the ionosphere, generate currents in the E-layer. The geomagnetic perturbations induced by these waves extend for long distances along the layer. These perturbations are recorded on the Earth's surface.

Moscow Engineering-Physical Institute, Moscow 115409. Translated from Prikladnaya Mekhanika i Tekhnicheskaya Fizika, Vol. 39, No. 6, pp. 21-26, November-December, 1998. Original article submitted October 31, 1994; revision submitted January 30, 1997.

A new mechanism for the generation of geomagnetic fluctuations by atmospheric electric dipoles was proposed recently [11, 12]. The essence of this mechanism is as follows. Various atmospheric processes (lightning discharges, absorption of gamma quanta from solar flares, and gamma bursts) result in spatial separation of charges with formation of an electric dipole of finite size. The characteristic lifetime of the dipole is from 0.1 to 1000 sec. The electric field generated by the dipole induces a system of ring currents in the gyrotropic layer of the ionosphere. These currents propagate by diffusion along the layer and generate quasistationary magnetic fields on the Earth's surface.

This mechanism of generation of geomagnetic perturbations is applicable in the case of underground and contact explosions. Let us consider a contact explosion (on the Earth's surface) with TNT equivalent W [ktons] [13]. The nuclear explosion generates a great amount of gamma quanta, half of which propagate predominantly radially in the upper half-space in the air for about 1 km from the center of the explosion. Inelastic scattering of gamma quanta by nitrogen and oxygen molecules gives rise to Compton electrons, which are emitted primarily forward and have a path length λ of about 4 m [14]. The Compton electrons produce additional ionization of the air, lose energy, and are almost instantaneously attached to neutral molecules. Thus, the following radial separation occurs inside the hemisphere: the positively ionized atoms originating from the Compton effect are located closer to the center of the explosion and the negatively ionized atoms produced by the attachment of Compton electrons to neutral molecules are farther from the center. The spacing between a pair of ions of opposite charge is equal to the path length of a Compton electron.

Some time after the nuclear explosion ($t > 10$ sec), the concentrations N [m^{-3}] of the positively and negatively ionized atoms produced by gamma quanta are almost equal (the electron concentration is negligibly small) [13]:

$$N = 1.3 \cdot 10^{12} \frac{(\xi(W)W)^{0.5}}{(t+2.66)^{0.6}}. \tag{1}$$

This expression is valid at the Earth's surface at a distance $R = 1$ km from the center of the explosion. Expression (1) is obtained with allowance for the fact that a Compton electron having an energy of 1 MeV forms $3 \cdot 10^4$ secondary electrons (the ionization potential is $\approx$30 eV) that do not participate in the formation of the electric dipole. Also, in expression (1) ion–ion recombination is used. The coefficient $\xi(W)$, which takes values from 0 to 1, gives the fraction of gamma quanta that participate in the formation of the atmospheric electrical dipole moment. The fact is that the thermal that is formed in tens of seconds rises upward and carries away part of the explosion products and radioactive dust [15]. Thus, the number of sources of gamma quanta decreases. Because of the complex pattern of gasdynamic flows in the nuclear explosion, it is not possible to calculate the coefficient $\xi(W)$ accurately. To estimate it, we use the fact that from 10 to 50% of the dust raised by a ground explosion with a TNT equivalent $W = 10^3$ ktons is ejected into the stratosphere at an altitude of more than 12 km [15]. This takes about 10^2–10^3 sec. Then, part of the dust is deposited back on the Earth's surface within a radius of several kilometers from the center of the explosion [16]. Therefore, the dimensions of the region in which the atmospheric electric dipole is formed are smaller than 10 km. Hence, it is assumed that at distances longer than 100 km from the center of the explosion, the dipole is point and the coefficient $\xi(W)$ is at least larger than 0.1.

The projection of the dipole moment onto the z axis directed from the center of the explosion vertically upward is roughly equal to $d = -(\pi/3)R^3 e\lambda N$, where e is the electron charge.

For $t \gg 10$, the time dependence of the dipole moment can be approximated with allowance for (1) by the delta function

$$d = -d_0 \Delta t \delta(t), \tag{2}$$

where $\Delta t = 10$ sec and $d_0 = 1.9 \cdot 10^2 \sqrt{\xi(W)W}$ [C·m].

The geomagnetic induction vector $\mathbf{B}_0$ makes angle α with the z axis. We direct the y axis of a rectangular Cartesian coordinate system along the Earth's surface to the north magnetic pole. Furthermore, we introduce a spherical coordinate system, in which the angle θ is reckoned from the z axis and the angle φ lies in a horizontal plane and is reckoned from the x axis. In the ionosphere layer at an altitude d km; the dipole moment $z_0 = 130$ m induces an electric field $\mathbf{E}$ with components

$$E_z = \frac{d}{4\pi\varepsilon_0}\,\frac{(3\cos^2\theta - 1)\cos^3\theta}{z_0^3}, \quad E_y = \frac{d}{4\pi\varepsilon_0}\,\frac{3\sin\theta\cos^4\theta}{z_0^3}\sin\varphi,$$
$$E_x = \frac{d}{4\pi\varepsilon_0}\,\frac{3\sin\theta\cos^4\theta}{z_0^3}\cos\varphi, \tag{3}$$

where ε_0 is the permittivity of vacuum.

The electric field excites electric conduction currents $\mathbf{j}$, which satisfy the Maxwell equations in a quasistationary approximation:

$$\operatorname{rot}\operatorname{rot}\sigma^{-1}\mathbf{j} + \mu_0\frac{\partial\mathbf{j}}{\partial t} = -\mu_0\frac{\partial\mathbf{j}_{\mathrm{ex}}}{\partial t}, \qquad \operatorname{div}\mathbf{j} = 0 \tag{4}$$

(μ_0 is the permeability of vacuum, σ is the conductivity tensor of the ionosphere, and $\mathbf{j}_{\mathrm{ex}} = \sigma\mathbf{E}$ is the extrinsic electric current).

Since, $\sigma_0 \gg \sigma_2 \approx \sigma_1$ in the ionospheric layer considered, the conductivity tensor in the Cartesian coordinates has the form

$$\sigma = \begin{pmatrix} \sigma_1 & \sigma_2\cos\alpha & -\sigma_2\sin\alpha \\ -\sigma_2\cos\alpha & \sigma_0\sin^2\alpha & \sigma_0\sin\alpha\cos\alpha \\ \sigma_2\sin\alpha & \sigma_0\sin\alpha\cos\alpha & \sigma_0\cos^2\alpha \end{pmatrix}. \tag{5}$$

Here σ_0 is the conductivity along the geomagnetic field, σ_1 is the Pedersen conductivity, and σ_2 is the Hall conductivity.

In the approximation of a thin layer (of thickness $h = 40$ km, which is much smaller than the horizontal dimensions), we introduce integral components of the current:

$$J_{x,y,z} = \int\limits_{z_0-h/2}^{z_0+h/2} j_{x,y,z}\,dz. \tag{6}$$

After simple transformations of (4) with allowance for (5) using the approximation $(\sigma_2/\sigma_1)\sin\alpha > 1$, we obtain

$$\cos^2\alpha\,\frac{\partial^2 J_x}{\partial x^2} + \frac{\partial^2 J_y}{\partial y^2} = \mu_0\sigma_3\left(\frac{\partial J_x}{\partial t} + \frac{\partial J_{x\,\mathrm{ex}}}{\partial t}\right),$$
$$\cos^2\alpha\,\frac{\partial^2 J_y}{\partial x^2} + \frac{\partial^2 J_y}{\partial y^2} = \mu_0\sigma_3\left(\frac{\partial J_y}{\partial t} + \frac{\partial J_{y\,\mathrm{ex}}}{\partial t}\right), \tag{7}$$
$$\mu_0\sigma_3\,\frac{\partial J_z}{\partial t} = -\sin\alpha\left(\frac{\partial^2}{\partial x^2} + \frac{\partial^2}{\partial y^2}\right)\left(\frac{\sigma_2}{\sigma_1}\,J_x + \cos\,\alpha J_y\right),$$

where $\sigma_3 = \sigma_2^2/\sigma_1 + \sigma_1$; $J_{x,\mathrm{ex}}$ and $J_{y,\mathrm{ex}}$ are introduced in the same manner as (6). At $x = y = 0$ and at infinity, the current components should vanish.

In the limiting case, where the force lines of the magnetic field are vertical (angle $\alpha = 0$ or $\alpha = \pi$), system (7) becomes the well-known equation [12]

$$\frac{\partial}{\partial r}\left(\frac{1}{r}\,\frac{\partial}{\partial r}(rJ(r,t))\right) = \mu_0\sigma_3\left(\frac{\partial J(r,t)}{\partial t} + \frac{\partial J_{\mathrm{ex}}}{\partial t}\right), \tag{8}$$

which is written for the ring current $J(r,t)$ ($J_x = -J\sin\varphi$ and $J_y = J\cos\varphi$) in the polar coordinates $r^2 = x^2 + y^2$.

Generally, using the affine mapping $x' = x/\cos\alpha$, $y' = y$, $J'_x = J_x$, and $J'_y = J_y\cos\alpha$, we reduce the first two equations of system (7) to Eq. (8) for the ring current $J'(r',t) = [(J'_x)^2 + (J'_y)^2]^{1/2}$:

$$\frac{\partial}{\partial r'}\left(\frac{1}{r'}\frac{\partial}{\partial r'}(r'J'(r',t))\right) = \mu_0\sigma_3\frac{\partial J'(r',t)}{\partial t}, \tag{9}$$

where $(r')^2 = (x')^2 + (y')^2 = x^2/\cos^2\alpha + y^2$.

Equation (9) with boundary conditions admits conservation of the magnetic dipole moment of the currents

$$M' = \int_0^\infty J'(r',t)\pi(r')^2 dr' = M'_{\text{ex}}, \tag{10}$$

where the moment of the extrinsic currents $M'_{\text{ex}} = M_{\text{ex}}/\cos\alpha$ is calculated using (3):

$$M_{\text{ex}} = \frac{h}{2}\int_{-\infty}^{\infty}\int_{-\infty}^{\infty}(xj_{y,\text{ex}} - yj_{x,\text{ex}})\,dx\,dy = -\frac{h\sigma_2 d(t)\cos\alpha}{2\varepsilon_0}.$$

We note that in the limiting case, the magnetic moment of the currents coincides with the expression derived earlier for the moment in a vertical geomagnetic field [11].

In the coordinate system x', y', the streamlines are circles $(x')^2 + (y')^2 = r_0^2$, where r_0 is an arbitrary radius, and in the coordinate system x, y, they are ellipses with major and minor semiaxes $b = r_0$ and $a = r_0\cos\alpha$. Thus, in the case of arbitrary slope α of the vector $\mathbf{B}_0$, electric currents propagate in a thin ionospheric layer along ellipses elongated from north to south. The angle α supplements the magnetic dip i. Therefore, for the majority of testing areas ($i > 60°$), $\cos\alpha > 0.8$ and the ellipsoidal streamlines can be replaced with good accuracy by circles.

To calculate the parameters of the geomagnetic signal on the Earth's surface, we use the results of [11], in which the time dependence of the dipole moment $d(t)$ is similar to (2). The currents obtained from Eq. (9) with allowance for conditions (10) form vertical and horizontal components of the quasistationary magnetic field on the Earth's surface. At a distance $\rho \gg z_0$ from the center of the contact explosion, the amplitude of the horizontal component is estimated by the formula

$$B_\rho = \frac{5}{\pi^2}\frac{h\sigma_2 d_0 \Delta t\cos\alpha}{\varepsilon_0\sigma_3\rho^5},$$

and the characteristic frequency of the signal is roughly $f = 4/(\mu_0\sigma_3\rho^2)$.

For an explosion with energy $W = 150$ ktons, $\xi(W) = 0.1$, and $\cos\alpha = 0.85$, the numerical values of the indicated quantities are $B_\rho = 0.006$ nT and $f = 3.2\cdot 10^{-3}$ Hz when $\sigma_2 = 4\cdot 10^{-4}$ S/m, $\sigma_3 = 10^{-3}$ S/m, and $\rho = 10^6$ m. We note that at smaller epicentral distances and for explosions with high energy release, the amplitudes of geomagnetic signals can exceed 1 nT. A geomagnetic signal with such parameters has two quasi-half-periods [11].

The mechanism proposed here for the generation of geomagnetic perturbations by electric dipoles makes it possible to clarify the process of formation of such perturbations at long epicentral distances from a contact explosion. The estimates given above are true for contact or underground explosions with radioactive emissions into the atmosphere. For deep underground explosions, the amplitude of such geomagnetic perturbations is much smaller, because the strong absorption of gamma quanta by ground decreases the dipole moment d_0. In the case of tests with decoupling, the amplitude can be decreased by a factor of V/R^3, where V is the volume of an air cavity in which the gamma quanta from the underground explosion propagate.

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