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Study of Seismo Effects in Electromagnetic Field and Ionosphere

Vasily Yu. Belashov

Kazan (Volga region) Federal University, 420008 Kazan, Russia
vybelashov@yahoo.com

Abstract. The results of study of displaying of seismic activity in variations of both the electromagnetic (EM) field and the basic ionospheric characteristics are presented. The 3D case is considered taking into account the effects of weak non-linearity, dispersion and dissipation in medium, that allows us to obtain more accurate results for both the near and far zones from the earthquake epicenter. In study of the seismic response in the EM field, it is shown that a precursor arises ahead the front of seismic wave, its amplitude decreases exponentially with distance. Regarding the response at ionospheric heights, the seismo-ionospheric post-effects have been studied, which are of great interest, in particular, for a better understanding of relationships in the system "solid Earth – atmosphere – ionosphere".

Keywords: Ionosphere, Electromagnetic Field, Earthquake, Precursor, Rayleigh Wave, IGW and TID Solitons.

1 Introduction

A number of experimental works starting from the 70s of the last century (see, e.g., [1, 2] and rather complete review [3]) reported the observation of low-frequency (LF) perturbations of the Earth's electromagnetic (EM) field a few seconds or minutes before the appearance of a seismic wave at a registration point. As possible reasons for this phenomenon, an assumption was made about the excitation in the *E*-layer of the ionosphere during an earthquake of a LF whistler propagating horizontally with a velocity of ~ 20 km/s or slightly slower (10 km/s and lower [3]). Another possible physical mechanism of the phenomenon is associated with the manifestation of the induction seismomagnetic effect in the earth's crust. In theoretical papers [4, 5] it was shown that both in the region of the medium's motion and in front of the front of the seismic wave, a system of currents and fields perturbing the Earth's EM field appears. In Sect. 2 we show that EM precursors are diffusive in nature, and obtain simple laws that determine the spatial size, characteristic duration and amplitude of the precursor.

It is necessary to note that the seismic effects are displayed also at heights of the ionosphere of the Earth. The issues of studying these effects in the ionospheric plasma caused by seismic phenomena are currently attracting the attention of researchers in connection with the importance of this problem not only for "pure" science, but also for ensuring the safe life of the population in seismically dangerous regions and on the planet as a whole. At the same time, an important role is played by the study of seismo-ionospheric post-effects, for example, to better understand cause-effect relationships in the system "solid Earth – atmosphere – ionosphere", for allocation of seismically caused oscillations in the spectrum of ionospheric fluctuations, etc. Sect. 3 presents the results of a theoretical study of the problem, taking into account weak nonlinearity, dispersion and the influence of dissipation in 3D geometry.

2 Seismo-Electromagnetic Effects

Consider a conducting homogeneous medium with a constant coefficient of electrical conductivity σ located in a uniform magnetic field $\mathbf{B}_0$. At time t=0, a spherically symmetric acoustic longitudinal wave arises. The quasistationary Maxwell equations (at $B \ll B_0$) have form: $\partial_t \mathbf{B} = D\Delta\mathbf{B} + \mathrm{rot}\left[\mathbf{v},\mathbf{B}_0\right]$, $\mu_0\,\mathrm{rot}\,\mathbf{B} = \sigma\left(\mathbf{E} + \left[\mathbf{v},\mathbf{B}_0\right]\right)$ where $\mathbf{v} = v(r,t)\,\mathbf{e}_r$ is the preset velocity field, $D = (\mu_0\sigma)^{-1}$ is the magnetic viscosity. We choose the spherical coordinate system (r, θ, φ) with the reference point at the center of symmetry. Then only three components of the field, B_r, B_θ, E_φ, which depend on the variables r, θ, t, will be nonzero. Let us study the solutions of the Maxwell equations for the far zone from the nidus ($r \gg R$, $r \gg r_d \gg \lambda$) and time $t \gg t^* = D/C_l^2$ (C_l is the longitudinal wave velocity). Analyzing solution near the front of the elastic wave at $r \sim C_l t$ we can obtain that for the front region ($\varepsilon \ge 0$) it has form [3, 5]

$$B_r = -\frac{2B_0 R\lambda G(t,\varepsilon)}{r^2}\left(1+\frac{\lambda}{r}\right)\cos\theta, \quad B_\theta = -\frac{B_0 R G(t,\varepsilon)}{r}\left(1+\frac{\lambda}{r}+\frac{\lambda^2}{r^2}\right)\sin\theta,$$
$$E_\varphi = \frac{B_0 R C_l G(t,\varepsilon)}{r}\left(1+\frac{\lambda}{r}\right)\sin\theta, \quad G = \exp\left(-\frac{\varepsilon}{\lambda}\right)\int_0^t \exp\left(-\frac{t'}{t_*}\right)\partial_t^3 f(t')\,dt'. \tag{1}$$

where $\lambda = D/C_l$, $t^* = D/C_l^2$, $\varepsilon = r - C_l t - R$ and $f(\xi)$ is the reduced elastic displacement potential. Behind the wave front, i.e. when $\varepsilon < 0$, the solution has form

$$B_r = -\frac{2B_0 R\lambda}{r^2 C_l}\left\{\left(1+\frac{\lambda}{r}\right)G_1(t,\varepsilon) + \partial_t^2 f\left(-\frac{\varepsilon}{C_l}\right) + \frac{C_l}{\lambda}G_2(\varepsilon,r)\right\}\cos\theta,$$

$$B_\theta = -\frac{B_0 R}{r C_l}\left\{\left(1+\frac{\lambda}{r}+\frac{\lambda^2}{r^2}\right)G_1(t,\varepsilon) + \left(1+\frac{\lambda}{r}\right)\partial_t^2 f\left(-\frac{\varepsilon}{C_l}\right) + \frac{C_l}{r}G_2(\varepsilon,r)\right\}\sin\theta,$$

$$E_\varphi = \frac{B_0 R C_l}{r}\left\{\left(1+\frac{\lambda}{r}\right)\left[\partial_t^2 f\left(-\frac{\varepsilon}{C_l}\right) + G_1(t,\varepsilon)\right] + \frac{C_l}{r}\partial_t f\left(-\frac{\varepsilon}{C_l}\right)\right\}\sin\theta, \tag{2}$$

$$G_1 = \exp\left(-\frac{\varepsilon}{\lambda}\right)\int_{-\varepsilon/C_l}^{t} \exp\left(-\frac{t'}{t_*}\right)\partial_t^3 f(t')\,dt', \qquad G_2 = \partial_t f\left(-\frac{\varepsilon}{C_l}\right) + \frac{C_l}{r} f\left(-\frac{\varepsilon}{C_l}\right).$$

Formulas (2) relate to the seismic zone, and formulas (1) describe the structure of the EM wave, a precursor. It follows from (1) that in the precursor region the field decreases exponentially with characteristic scale λ. This result can be explained as follows. Since the precursor has a diffusion character, that the characteristic diffusion propagation velocity $d_t\, r_d \sim (D/t)^{1/2}$ should be of the order of the velocity of the source of geomagnetic disturbances. We can find from here the characteristic duration $t^* \sim D/C_l^2$ and spatial scale $\lambda \sim C_l t^* \sim D/C_l$ of the EM precursor.

At long distances ($r \gg R$), the expression for a longitudinal spherical wave is a combination of two half-waves: compression and rarefaction, and we can obtain [5]

$$\frac{B_\theta}{A} = \begin{cases} \exp\left(-\dfrac{\varepsilon}{\lambda}\right)\left[v_1 - (v_1 + v_2)\exp\left(-\dfrac{\tau_1}{t_*}\right) + v_2 \exp\left(-\dfrac{\tau_1+\tau_2}{t_*}\right)\right], & \varepsilon \ge 0; \\ \exp\left(-\dfrac{\varepsilon}{\lambda}\right)\left[v_2 \exp\left(-\dfrac{\tau_1+\tau_2}{t_*}\right) - (v_1+v_2)\exp\left(-\dfrac{\tau_1}{t_*}\right)\right] + v_1, & 0 > \varepsilon \ge -C_l\,\tau_1; \\ v_2\left[\exp\left(-\dfrac{\varepsilon}{\lambda} - \dfrac{\tau_1+\tau_2}{t_*}\right) - 1\right], & -C_l\,\tau_1 > \varepsilon; \end{cases}$$

$$E_\varphi = -B_\theta C_l; \qquad A = -B_0 R \sin\theta/(rC_l). \tag{3}$$

As for the amplitude of magnetic field of precursor B^* in the far zone, we can obtain [3]: $B^* = -B_\theta(0) = B_0 R \mu_0^2 \sigma^2 C_l^3 v_1 \tau_1(\tau_1 + \tau_2)\sin\theta/(2r)$. An analysis of (3) shows that when passing from the precursor region ($\varepsilon > 0$) to the focal point ($\varepsilon < 0$), B_θ changes its sign, and the magnitude of the field reaches to its maximum amplitude $B_{\max} = B_\theta(-C_l\,\tau_1) = B_0 R \mu_0 \sigma C_l v_2 \tau_2 \sin\theta/r$ at $\varepsilon = -C_l\,\tau_1$. This represents the amplitude of the main signal that occurs after the arrival of a seismic wave to the observation point, i.e. the amplitude of the induction seismomagnetic effect. From here, we obtain: $B^*/B_{\max} = [\mu_0 \sigma C_l^2 v_1 \tau_1(\tau_1+\tau_2)]/2v_2\tau_2 \sim l/\lambda = (\tau_1+\tau_2)/t_* \ll 1$ where $l = C_l\,(\tau_1+\tau_2)$ is the acoustic wavelength, and λ is the precursor wavelength.

The results obtained can be explained as follows. A seismic wave generates external currents with a density $\mathbf{j}_{cm} = \sigma\left[\mathbf{v}, \mathbf{B}_0\right]$. Expressions (1) give the field of the effective magnetic moment $\mathbf{p}_m$ taking into account the screening arising due to the skin effect. Assuming $\sigma \to 0$, we obtain: $B_r = -2G_3\lambda^2 r^{-3}\cos\theta$, $B_\theta = -G_3\lambda^2 r^{-3}\sin\theta$, $G_3 = (B_0 R/C_l)\partial_t^2 f(t)$, whence it is seen that $\mathbf{p}_m = -4\pi G_3 \lambda^2 \mathbf{B}_0/(B_0\mu_0)$. The minus sign here is due to the diamagnetic effect of a moving conducting medium, therefore, the projections of magnetic disturbances at long distances from the epicenter are negative and the EM precursor signal is also negative.

3 Manifestation of Seismic Effects in the Ionosphere

When considering the acoustic disturbance in the near zone of earthquake, we can obtain the approximate expression for the perturbation of electron density from the continuity equation as [5]:

$$
\begin{aligned}
N_e'(t,z,r,\varphi) \approx\ & (2\pi R)^{-1} i\, N_0(z)\cos\alpha \int_{-\infty}^{\infty} \frac{d\omega}{\omega}\Gamma(\omega,z,r)\times \\
& \times\left[1/2H(z') + i\,\varepsilon\,(\omega,R)\sin\chi / c\,(z')\right] - \\
& -(2\pi R)^{-1} i N_0(z)\sin\alpha \int_{-\infty}^{\infty}\frac{d\omega}{\omega}\Gamma(\omega,z,r)\times i\,\varepsilon\,(\omega,R)\cos\chi / c\,(z'),
\end{aligned} \tag{4}
$$

$$
\begin{aligned}
\Gamma(\omega,z,R) =\ & \mathrm{e}^{-i\omega t}\,V_0(\omega)\left[-R_0(\omega,R)\cos\alpha + R_1(\omega,R)\cos\varphi\cos\alpha\right]\times \\
& \times\exp\left\{\int_0^z dz'/2H(z') + i\int_0^R dR'\,\varepsilon(\omega,R')/c(R')\right\}
\end{aligned}
$$

and φ is the angle between the planes $(\mathbf{z}, \mathbf{H}_0)$ and $(\mathbf{z},\mathbf{V})$.

To obtain quantitative estimates of the magnitude of perturbations of the electron density in the ionosphere *F*-layer caused by non-stationary oscillations of the earth's surface as a result of an earthquake, we performed calculations in accordance with formula (4) for various spatial scales of the earthquake L for three types of approximation of the displacement velocity of the earth's surface: $V_0(t) = S_1\,\beta_1^2\,t\,\exp(-\beta_1 t)$; $V_0(t) = 2S_2\,\Theta_1\beta_2\,t\,\exp\Theta_1,\ \Theta_1 = 1-\beta_2 t^2$; $V_0(t) = \frac{1}{4}S_3\,\Theta_2\beta_3^2\,t\,\exp\Theta_2,\ \Theta_2 = 2-\beta_3 t.$

The first approximation corresponds to earthquakes, which lead to an increase or decrease of the level of the earth's surface with maximum amplitude S_1 at point $r = 0$. Two other approximations describe earthquakes accompanied by oscillations of the earth's surface with different relaxation times.

We have obtained that the ionosphere response is quasiperiodic in nature with oscillation periods about 40–80 s, moreover, the amplitude of the response substantially depends both on the temporal nature of the initial disturbance of the earth's surface and on its spatial scale. This can be explained by the filtering properties of the atmosphere with a frequency band from the acoustic cutoff frequency ω_a to the upper frequency, which is defined by the viscosity of the atmosphere. The amplitude of the perturbation decreases and the quasi-period increases with distance.

As for a far earthquake zone, that the Rayleigh wave $V_z\big|_{z=0} = d_t Z(r',t)$, $Z(r',t) = h(t)\exp[-(r')^2/L^2]$ (here $(r')^2 = \xi^2 + y^2,\ \xi = x - v_R\,t,\ v_R$ is the velocity of the wave) leads to the formation of a wave going upward with an amplitude growing with height, which is associated with an exponential decrease of density: $\rho_0(z) = \rho_0(0)\exp(-z/H)$. Nonlinear effects begin to manifest themselves at the heights of the ionosphere *F*-region, when a nonlinear solitary IGW is formed under the action of the going upword wave excited by the surface Rayleigh wave [6]. Taking into account the geometry of the problem and weak nonlinearity for the velocity of neutral particles $u(t,r',z) = V(t,r,z)\big|_{x=\xi+vt}$ at $\partial_z = 0$, we obtain the BK equation [6, 7]:

$$
\partial_t u + \frac{2\gamma-1}{\gamma^2}u_z\partial_\xi u - \sigma\partial_\xi^2 u + 2\frac{(\gamma-2)^2}{\gamma^2}vH\,\partial_\xi^3\left[u + \frac{(\gamma-2)^2}{2\gamma^2}\varepsilon H^2\,\partial_\xi^2 u\right] = \frac{v}{2}\int_{-\infty}^{\xi}\partial_y^2 u\,d\xi \tag{5}
$$

where $\gamma = C_p/C_v,\ \varepsilon = -v/v_{\min}^{ph},\ v_{\min}^{ph}$ is the minimum phase velocity of linear oscillations, σ is the viscosity coefficient. Considering the solitary waves traveling at the near-to-horizontal angles, we can obtain the solution of the continuity equation for the electron density N_e in the F-layer [6, 7] as follow:

$$N_e(u,t) = N_e(u,t_0)\exp\left[\Im(u,t)\right], \qquad \Im(u,t) = \int_{t_0}^{t} g(u,t)\,dt\,, \tag{6}$$

$$g(u,t) = C - \left(1/H_i + 1/2H\right) f(u,t), \qquad C = 3a/H_i^2 - \beta(1-q),$$

$$f(u,t) = uc\exp(z/2H)\left(1 - \mathrm{e}^{-\upsilon t'}\right)\sin I\cos I, \qquad q = Q/\beta N_e, \qquad a = D_\alpha \sin^2 I\,.$$

where $D_0\exp(z/H_i) = D_\alpha \sin^2 I$, D_α is the ambipolar diffusion coefficient, $\beta = \beta_0\,(-Pz/H_i)$ and Q are, respectively, the recombination rate and the ion production rate; $t' = t - t_0$ where t_0 is the moment of the start of the neutral component's perturbation; H_i is the scale height for ions. Function u in solution (6) satisfies Eq. (5).

The results of integration of Eqs. (5), (6) for typical values of the parameters of the F-layer and the disturbances travelling with the velocities ~ 200 ms^{-1}, were presented in our papers and book [5-7]. It was shown there that for $N' = \left\{\left[N(u,t) - N(0,t)\right]/N(0,t)\right\}\times 100\%$ function $N'(u,t)$ has a wave character with an increasing steepness of the leading front like a shock wave. Thus, such TID excited by the Rayleigh wave can be consider as some post-effect of the earthquake.

4 Discussion

The analysis presented in Sect. 2 shows that an EM precursor appears in front of the seismic wave front in a conducting medium, and the precursor amplitude exponentially decreases with distance, with a characteristic scale $\lambda = (\mu_0 \sigma C_l)^{-1}$. For the upper layer of sedimentary rocks, λ~100 km, therefore, the precursor can be ahead of the elastic wave by no more than a few seconds. The precursor amplitude increases with time up to the moment of arrival of the seismic wave. At distances of the order of tens of kilometers from the epicenter, its amplitude can reach values from several pT to nT for magnetic disturbances and from several nV/m to μV/m for electric ones, depending on the medium conductivity and seismic wave parameters. With increasing conductivity, the precursor amplitude increases, and its characteristic size λ decreases.

As for the seismic effects in the ionosphere in near and far zones from the nidus of earthquake (Sect. 3), note that the study of the multidimensional case, taking into account all significant factors (weak nonlinearity, dispersion and dissipation), allows us to obtain more accurate results for both the near and far zones of epicenter. Thus, for a few types of approximation of the displacement velocity of the earth's surface it was shown that in the near zone the ionosphere response is quasiperiodic with oscillation periods about 40–80 s, and its amplitude depends on temporal and spatial scales of the initial disturbance of the earth's surface. At this, the amplitude decreases and the quasiperiod increases with distance. On big distances it is necessary to take into account that spatial dispersion leads to damping of the oscillations of the acoustic branch with propagation and a shift of the spectral maximum to a lower-frequency region is observed. In this case, the surface Rayleigh wave excites the perturbation of the neutral component of the atmosphere in form of a solitary IGW which is a source of the solitary TID at heights of the *F*-layer of the ionosphere. Nonlinear effects lead to increasing steepness of the TID leading front, and dissipation leads to the exponential decay of the perturbation with decreasing its amplitude.

5 Conclusions

In conclusion, we have presented the results of study of displaying of seismic activity in variations of both the EM field and the basic ionospheric characteristics. We have showed that considering of the 3D case with a due account of the effects of weak nonlinearity, dispersion and dissipation in medium enables to obtain more accurate results for both the near and far zones of the earthquake epicenter. In study of the seismic response in the EM field, it was confirmed that a precursor arises ahead the front of seismic wave, and it was shown that its amplitude depends on the medium conductivity and the parameters of the wave. Regarding the response at ionospheric heights, the seismo-ionospheric post-effects were studied, that is of great interest, in particular, for a better understanding of relationships in the system "solid Earth – atmosphere – ionosphere" and for identification of seismically caused oscillations in the spectrum of the ionospheric fluctuations, etc. The effect of the acoustic impulse caused by the Rayleigh wave on the ionosphere's neutral component near the epicenter was also considered, and formation of the solitary IGWs and the TIDs, which are caused by it, at heights of the F-layer in the far zone was studied.

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