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Review Article

Manifestation of Seismic Activity in Variations of the EM Field and Basic Ionospheric Characteristics

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Abstract

The theoretical analysis of manifestation of seismic events in the electromagnetic field and fluctuations of the ionospheric parameters is presented. The three-dimensional case is investigated with due account of nonlinear, dispersive and dissipative properties of a medium. This give us a possibility to conduct more accurate study of influence of seismic activity in near and far zones of the epicenters of the earthquakes. It is demonstrated that EM response, as some precursor of the seismic event, can be observed ahead the seismic wave front, and its amplitude exponentially decreases with propagation. As for the ionospheric response, the post-effects at ionospheric heights are studied. It is very important for understanding and explaining of relations in the Earth – atmosphere – ionosphere system.

Keywords: EM Field; Ionosphere; Seismic Event; Rayleigh Wave; Solitons; Internal Gravity Wave; Travelling Ionospheric Disturbance

Introduction

Over the past five decades, a fairly large number of experimental works, in which the presence of responses of seismic events in the EM field was noted, have been published (see, e.g., [1,2] and rather complete review [3]). Thus, it has been noted that the low-frequency disturbances in the electromagnetic field a few seconds or minutes before arrival of the Rayleigh wave to registration point arise. To explain this effect, the assumption that during earthquake a low-frequency whistler, which propagates in a horizontal plane with the ~ 20 km/s velocity or slightly slower [3], is excited in the ionosphere E-layer. The manifestation of the induction seismoelectromagnetic effect in the earth's crust is sometimes considered as another possible physical mechanism of this phenomenon (see, for example, theoretical papers [4,5] where a possibility of appearance of a system of currents and EM fields as the consequence of the medium's motion in a region and before the front of seismic wave leads to perturbation of the natural Earth's electromagnetic field). In the next section it is shown the diffusive nature of the EM precursors, and presented some simple laws determining the temporal and spatial characteristics of the such precursors.

It should be noted that the effects of seismic events are manifested also at the Earth ionosphere's heights. The investigation of the seismically caused responses in a plasma of the ionosphere are important not only for "pure" science, but also for ensuring a population safety in the regions with seismically dangerous and also on the planet as a whole. Note that from a fundamental point of view, the study of seismic-ionospheric post-effects is also very important, for example, to elucidate the mechanism of cause-and-effect relationships in the "solid Earth – atmosphere – ionosphere" system, that will make it possible to more clearly distinguish seismically caused oscillations in a wide spectrum of ionospheric oscillations, etc. In Sect. 3 the results of theoretical investigation of the seismically caused effects at heights of the ionosphere with a due account of weak nonlinearity, dispersion and dissipation in a medium are presented, in 3D geometry.

Manifestation of seismic effects in the EM field

We will assume that the propagation medium is conductive (conductivity coefficient σ=const) and uniform, and the magnetic field $\mathbf{B}_0$ is uniform. Let an acoustic spherically symmetric longitudinal wave arises at time t=0. The field is described by the following quasistationary Maxwell equations (where $B << B_0$):

$$\partial_t \mathbf{B} = D\Delta\mathbf{B} + \mathrm{rot}\left[\,\mathbf{v},\mathbf{B}_0\,\right], \quad \mu_0\,\mathrm{rot}\mathbf{B} = \sigma\left(\mathbf{E} + \left[\,\mathbf{v},\mathbf{B}_0\,\right]\right) \qquad (1)$$

with velocity $\mathbf{v} = v(r,t)\,\mathbf{e}_r$ and magnetic viscosity $D = (\mu_0\sigma)^{-1}$. In spherical coordinates (r, θ, φ) with the reference point located in the center of symmetry of the system, only three field components, B_r, B_θ, E_φ, which are the functions of r, θ, t, are nonzero. Consider the solutions of Eqs. (1) in the far zone of the earthquake nidus (where $r >> R$, $r >> r_d >> \lambda$) at time $t > \; t^* = D / C_l^2$ where C_l is the longitudinal wave velocity. In this case, near the elastic wave front at $r \sim C_l t$ we can obtain the solution in the front area (where $\varepsilon \ge 0$) in the following form [3,5]:

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

$$B_\theta = -\frac{B_0 R G(t,\varepsilon)}{r}\left(1 + \frac{\lambda}{r} + \frac{\lambda^2}{r^2}\right)\sin\theta, \qquad (2)$$

$$E_\varphi = \frac{B_0 R C_l G(t,\varepsilon)}{r}\left(1 + \frac{\lambda}{r}\right)\sin\theta,$$

$$G = \exp\left(-\frac{\varepsilon}{\lambda}\right)\int_0^t \exp\left(-\frac{t'}{t_*}\right)\partial_t^3 f(t')\,dt'.$$

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

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

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

$$E_\varphi = \frac{B_0 R C_l}{r}\left\{\left(1 + \frac{\lambda}{r}\right)\left[\partial_t^2 f\left(-\frac{\varepsilon}{C_l}\right) + G_1(t,\varepsilon)\right] + \frac{C_l}{r}\partial_t f\left(-\frac{\varepsilon}{C_l}\right)\right\}\sin\theta, \qquad (3)$$

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

Solutions (3) describe field in the seismic zone, and solutions (2) reflect the EM wave structure, i.e. a precursor. As one can see from (2), in the precursor region the EM field decreases exponentially with characteristic scale λ, and this result is explained as follows. The EM precursor has a diffusion character, therefore the characteristic propagation velocity of diffusion $d_t\, r_d \sim (D/t)^{1/2}$ should be of the order of the velocity of the geomagnetic disturbances' source. In this case, it is easy to find the characteristic duration and spatial scale of precursor: $t^* \sim D / C_l^2$ and $\lambda \sim C_l\, t^* \sim D / C_l$.

For distances $r > \;R$ the result for a spherical longitudinal wave is the combination of the half-waves of compression and rarefaction, and in this case we obtain [5].

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

$$E_\varphi = -B_\theta C_l; \qquad A = -B_0 R\sin\theta/(rC_l). \qquad (4)$$

As for the amplitude of the precursor's magnetic field B^* in the earthquake far zone, we obtain [3]: $B^* = -B_\theta(0) = B_0 R\mu_0^2\sigma^2 C_l^3 v_1\tau_1(\tau_1+\tau_2)\sin\theta\,(2r)$. It follows from (4) that with passing from the region of precursor (where $\varepsilon > 0$) to the focal point (where $\varepsilon < 0$), magnetic field B_θ changes its sign, and the field's amplitude reaches to its maximum value $B_{\max} = B_\theta(-C_l\tau_1) = B_0 R\mu_0\sigma C_l v_2\tau_2\sin\theta / r$ at $\varepsilon = -C_l\tau_1$. This is the main signal that is observed after the seismic wave arrival to the point of observation, and its amplitude reflects the induction seismomagnetic effect. We can obtain from here:

$$B^*/B_{\max} = [\mu_0\sigma C_l^2 v_1\tau_1(\tau_1+\tau_2)]\;/\,2v_2\tau_2 \sim l/\lambda = (\tau_1+\tau_2)/t_* < \; 1$$

$$(\,l = C_l(\tau_1+\tau_2)$$

is a wavelength of acoustic wave, and λ is the wavelength of precursor.

We explain the obtained results as follows. A seismic wave excites external currents with density $\mathbf{j}_{cm} = \sigma\left[\,\mathbf{v},\mathbf{B}_0\right]$. Relations (2) describe the field of the effective magnetic moment $\mathbf{p}_m$ with due account of screening arising as a result of the skin effect. Assuming that $\sigma \to 0$, we obtain from (2) the expressions: $B_r = -2G_3\lambda^2 r^{-3}\cos\theta$, $B_\theta = -G_3\lambda^2 r^{-3}\sin\theta$, $G_3 = (B_0 R / C_l)\,\partial_t^2 f(t)$, and one can see from here that $\mathbf{p}_m = -4\pi G_3\lambda^2\mathbf{B}_0\,(\,B_0\mu_0)$. The minus sign appears here due to the diamagnetic effect at movement of the conducting medium; therefore, the components of the magnetic field of disturbances at large distances from the earthquake epicenter are negative, and the signal of the EM precursor is also negative.

Ionospheric manifestation of seismic events

Considering the effect in the near earthquake's zone, we obtain from the continuity equation the following approximate expression for the perturbation of electron density [5]:

$$N_e'(t,z,r,\varphi) \approx (2\pi R)^{-1} i N_0(z)\cos\alpha \int_{-\infty}^{\infty} \frac{d\omega}{\omega}\Gamma(\omega,z,r)\times \times\left[1/2H(z') + i\varepsilon(\omega,R)\sin\chi/c(z')\right] - \tag{5}$$

$$-(2\pi R)^{-1} i N_0(z)\sin\alpha \int_{-\infty}^{\infty} \frac{d\omega}{\omega}\Gamma(\omega,z,r)\times i\varepsilon(\omega,R)\cos\chi/c(z'),$$

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

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

To obtain, in accordance with formula (5), quantitative estimates of the magnitude of electron density disturbances in the *F*-layer of the ionosphere, excited by oscillations of the earth's surface caused by earthquakes of various spatial scales *L*, we considered three types of approximation of the rate of displacement of the earth's surface:

$$V_0(t) = S_1\beta_1^2 t\ \exp(-\beta_1 t);\ V_0(t) = 2S_2\Theta_1\beta_2 t\ \exp\Theta_1,$$

$$\Theta_1 = 1-\beta_2 t^2;\ V_0(t) = \tfrac{1}{4}S_3\Theta_2\beta_3^2 t\ \exp\Theta_2,\ \Theta_2 = 2-\beta_3 t.$$

The first approximation relates to earthquakes leading to increasing or decreasing the level of the earth's surface at point r = 0 with maximum amplitude S_1. The second and third approximations correspond earthquakes leading to oscillations of the earth's surface with different times of relaxation.

Our calculations in accordance with Eq. (5) showed that the ionospheric response to an earthquake in the near zone has a quasiperiodic character with periods ~40-80 s, and the response amplitude depends significantly on both the temporal and spatial scales of the initial disturbance of the earth's surface. This is explained by the atmosphere's filtering properties in range from the acoustic cutoff frequency to frequency determining by the atmospheric viscosity. We observe decreasing of the amplitude and increasing of the quasiperiod of the disturbance with distance.

In a far zone of earthquake, the Rayleigh wave

$$V_z\big|_{z=0} = d_t Z(r',t),\ Z(r',t) = h(t)\exp[-(r')^2/L^2]$$

where $(r')^2 = \xi^2 + y^2$, $\xi = x - v_R t$, v_R is the wave velocity, excites an upward wave in the surface layer of the atmosphere, and its amplitude increases with height due to the exponential decrease in density: $\rho_0(z) = \rho_0(0)\exp(-z/H)$. Nonlinear effects start to manifest themselves at heights of the F-region of the ionosphere, where an upward wave excited by a Rayleigh surface wave transforms into a nonlinear solitary internal gravity wave (IGW) [6]. Considering this IGW we can obtain for the neutral particles' velocity $u(t,r',z) = V(t,r,z)\big|_{x=\xi+vt}$ for $\partial_z = 0$ the BK equation[1] [6,7]:

$$\partial_t u + \frac{2\gamma-1}{\gamma^2}u\,\partial_\xi u - \sigma\partial_\xi^2 u + 2\frac{(\gamma-2)^2}{\gamma^2}vH\partial_\xi^3 \left[u + \frac{(\gamma-2)^2}{2\gamma^2}\varepsilon H^2\partial_\xi^2 u\right] = \frac{v}{2}\int_{-\infty}^{\xi}\partial_y^2 u\,d\xi \tag{6}$$

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

$$N_e(u,t) = N_e(u,t_0)\exp\left[\Im(u,t)\right],\qquad \Im(u,t) = \int_{t_0}^{t} g(u,t)\,dt, \tag{7}$$

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

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

where $D_0\exp(z/H_i) = D_\alpha\sin^2 I$, D_α is the coefficient of ambipolar diffusion, $\beta = \beta_0(-Pz/H_i)$ is the recombination rate, and Q is the ion production rate; $t' = t - t_0$, and t_0 is the moment of the start of perturbation of the neutral component; H_i is the scale height for ions. Function *u* in (7) satisfies Eq. (6).

As it was shown in our papers and book [5-7] by integrating Eqs. (6), (7), for disturbances propagating with velocities ~ 200 ms^{-1} at typical values of the *F*-region parameters, function $N'(u,t) = \{[N(u,t) - N(0,t)]/N(0,t)\}\times 100\%$ has the form of a solitary wave with a steep its leading front like a shock wave. Thus, such travelling ionospheric disturbances (TID) excited by the Rayleigh wave can be considered as a post-effect of the earthquake.

[1]The Belashov-Karpman equation

Discussion and Conclusion

Our analysis of the results which is presented in Sect. 2 enables us to conclude that in conducting medium the EM precursor with characteristic scale $\lambda = (\mu_0 \sigma C_l)^{-1}$ arises before the seismic wave front and its amplitude decreases exponentially with a distance from a nidus. Since it is known that for the upper layer of sedimentary rocks λ~100 km, it can be concluded that the precursor will advance the elastic seismic wave by no more than a few seconds.

It should be noted that the precursor amplitude increases with time up to the moment when the seismic wave arrives at the observation point. In dependence on a medium conductivity and the characteristics of a seismic wave, the precursor amplitude at distances of tens kilometers from the epicenter can take values from several pT to nT for magnetic disturbances and from several nV/m to μV/m for electrical ones. The precursor amplitude increases and its characteristic size decreases at increasing conductivity of the propagation medium.

As to the earthquakes' effects at the ionospheric heights in both near and far zones from a nidus (see Sect. 3), it is necessary to note that the investigation of the 3D case with a due account of such medium properties as nonlinearity, dispersion and dissipation gives us a possibility to obtain more accurate results for both the near and far zones from the earthquake epicenter. In Sect. 3 we showed for a few models of seismic displacement of the earth's surface that in the near zone the ionospheric response is quasiperiodic with the period of oscillations ~40-80 s, and its amplitude depends on the both temporal and spatial scales of displacement and decreases with distance, while the quasiperiod increases.

We also showed that at big distances it is necessary to take into account the fact that spatial dispersion leads to damping of the acoustic branch's oscillations with propagation, that leads to a shift of the spectral maximum towards lower frequencies. At this, in the far zone, the Rayleigh surface wave excites the disturbance in the neutral component of the atmosphere in the form of a solitary IGW, and this IGW is a source of a solitary TID at heights of the ionosphere's F-layer. In accordance with the BK equation (6), nonlinear effects lead to increasing of steepness of the TID leading front, and the dissipation leads to exponential damping of the disturbance amplitude with its further propagation.

So, we have presented here our results of theoretical analysis of manifestation of seismic events in the EM field and in variations of the basic ionospheric parameters including the electron density. We have showed in the paper that a three-dimensional approach to the study of the problem, with due account the effects of nonlinearity, dispersion and dissipation in the medium where the wave propagates, makes it possible to obtain more accurate results both for near and far zones from the epicenter of earthquake. So, when studying the seismic response in an electromagnetic field, we have confirmed that the precursor appears ahead of the front of the seismic wave, and showed that its amplitude depends on the conductivity of the medium and the wave parameters.

As to a seismic response at heights of the ionosphere, we have studied the seismo-ionospheric post-effects, which are important, in particular, for a better understanding of the mechanism of relationships in the "solid Earth – atmosphere – ionosphere" system and for distinguishing the seismically caused fluctuations in a full spectrum of the ionospheric oscillations. We have also considered the effect of the acoustic impulse caused by the Rayleigh wave on a neutral component of the ionosphere near the earthquake epicenter, and further formation of the caused by it IGWs and TIDs of the electron density of soliton type at heights of the F-region of ionosphere in a far zone from the earthquake nidus.

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