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Model for the VLF/LF radio signal anomalies formation associated with earthquakes

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Abstract

The influence of quasi-static electric field of seismic origin on the characteristics of the internal gravity waves (IGWs) in the Earth's ionosphere is considered. The electric field in the ionosphere arises due to the injection of charged aerosols into the atmosphere, formation of an EMF in the near Earth atmosphere and perturbation of the conductive electric current in the global electric circuit. Amplification of the electric current in seismic zone is accompanied by the formation of perturbation of the lower ionosphere that affects the amplitude and phase of VLF/LF signals. The action of the electric field on the IGWs is connected with the appearance of the Ampere's force in the ionosphere. In the spectral range of these waves the latter acts on the neutral component of the ionosphere plasma. As the result of this interaction the ionosphere starts to support the discrete spectrum of oscillations. Periods of their maximums increase as numbers of natural sequence. The existence of such peculiarities of the waves in the ionosphere is confirmed by observations.

Keywords: Electric field; Ionosphere; Earthquakes; Ampere's force; Internal gravity waves; Discrete spectrum

1. Introduction

For the study of long term ionosphere dynamics a special well tested radio-physical methods are used. In some studies (e.g., Biagi et al., 2004; Rozhnoi et al., 2005, 2007; Hayakawa 2007) the specific variations of the amplitude and phase of VLF signals were observed the traces of which were close to the epicentres of the forthcoming earthquakes. The transmitters and receivers of these waves ((20–50) kHz) propagating in the Earth-ionosphere waveguide were located on the ground. Such anomalies arise before earthquakes with magnitudes $M > 3$ 3–10 days before the event. The character of propagation of VLF/LF (VLF, 3–30 kHz, LF, 30–300 kHz) signals in the Earth-ionosphere waveguide is defined on one hand by the electric conductivity of the Earth's surface and on the other hand by the conductivity of the lower ionosphere. The conductivity of the Earth's surface is smaller subject to variation. The observed perturbations in the signal are mostly depend on the height of reflection. The latter mainly depends on the value of the electron density and its gradient near the boundary of the lower ionosphere. The review of the action of seismic processes on the lower ionosphere was given by Hayakawa (2007). This author presented the proofs of existence of the ionosphere perturbations related to the earthquakes using statistical analysis and separate case studies.

The change in the position of the characteristic minimums in the diurnal course of phase and amplitude during sunrise and sunset a few days prior strong earthquakes in Japan was presented in the papers (Hayakawa et al., 1996; Molchanov and Hayakawa, 1998). Biagi et al. (2004) gives the data of the signal level in the VLF/LF frequency range propagating along the five traces. The explicit decreases in the signal intensity before the earthquake epicenters which were close to the traces of the signals were

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found. Rozhnoi et al. (2005) analyzed the signals of transmitter (40 kHz) located in Japan from 01.07.2004 to 24.01.2005. The receiver was in Kamchatka. The series of earthquakes appeared during this time near the signal propagation trace. It was shown that during a few days prior the earthquakes in each series there were anomalies in the form of the decreases of the amplitude and phase of the signals. The spectra of perturbations were analyzed. It was shown that in the spectra of quiet as well as disturbed days the main maximums correspond to the period of 30–35 min. Moreover, during seismic activity there is an evidence of appearance of maximums with 20–25 min and 10–12 min. It should be noted that analysis of spectra of amplitude and phase variations during magnetosphere substorms does not reveal such an effect. Rozhnoi et al. (2007) presented observations of VLF/LF amplitude and phase perturbations propagating along three wave traces together with DEMETER satellite data during two periods of seismic activity in Kamchatka–Japan region. The explicit anomalies in the characteristics of signals on the ground and onboard the satellite during period of seismic activity were found. The analysis of signals carried out by Rozhnoi et al. (2009) from the same transmitters along intersecting traces during L'Aquila (Italy) earthquake 06.04.2009 allowed for the first time to locate the region of the earthquake preparation.

At present it is generally accepted that action of seismic processes on the ionosphere plasma is carried out basically by means of the internal gravity waves (IGWs) and electric field. Gokhberg and Shalimov (2000) analyzed existing experimental data collected during the final phase of the earthquake preparation. These authors considered that appearance of the ionosphere inhomogenities during this time is considered with propagation of IGWs through ionosphere. The source of these waves can be long term Earth's eigen oscillations, the local green house effect and nonstationary gas injection from the lithosphere. Molchanov et al. (2004) suggested a scenario for the phenomena in the atmosphere and ionosphere. These authors considered that perturbation of the temperature and density of the atmosphere arises as the result of upward lift of the hot water and gases in the lithosphere before the earthquake. Mareev et al. (2002) considered the appearance of the ionosphere turbulence due to the upward propagation IGW generated by these random sources located on the earth's surface. During interpretation of earthquake precursors in the framework of the IGWs propagation one faces some difficulties. These waves propagate under certain angle to the Earth's surface. The larger period the smaller is the angle. IGWs attain the ionosphere at the distance of the order of 1000 km from the earthquake epicenter. Furthermore, one observes the ionosphere and electromagnetic perturbations localized in the vicinity of the epicenter. Observed by Rozhnoi et al. (2005) characteristic periods (10–12 and 20–25 min) for the maximums of the amplitude and phase spectra of the signals of the transmitter with the frequency 40 kHz, arising in the process of earthquake preparation, it is hard to explain in the framework of IGWs propagation into the ionosphere. The increase of IGWs intensity before earthquake cannot be the cause of their vertical propagation into the ionosphere and appearance of short period spectral lines in the ionosphere oscillations. The aim of the paper is to interpret mentioned above observations of the ionosphere perturbations before earthquakes on the base of the model developed by Sorokin and Pokhotelov (2010). This model assumes the influence of the electric field of seismic origin on the propagation of IGWs.

2. Mechanism of the lower ionosphere modifications

Perturbation of the conductive current in the global circuit above the seismic region triggers modification of the altitude profile of the electron concentration. The latter may be the cause of the appearance of anomalies of the signals in the VLF/LF frequency range. As a confirmation of such possibility may serve the data obtained by Fuks and Shubova (1994) during Chernobyl accident. It was shown that strong discharges of the radioactive substances and aerosols into the atmosphere was accompanied by variation of the phase and amplitude of the VLF signal along the propagation trace that passes the region of the accident. Analysis carried by Martynenko et al. (1996) showed that such perturbations of the characteristics of the VLF propagation may arise due to the increase of the electric field in the lower ionosphere boundary up to the value $\sim$1 V/m.

The detailed studies of quasi-static electric fields in the ionosphere with the help of satellite observations above seismic regions have been carried out in numerous papers (e.g., Chmyrev et al., 1989; Gousheva et al., 2006; Gousheva et al., 2008; Gousheva et al., 2009). A large number of seismic events have been analyzed with the aim to identify the processes of anomalous amplification of the electric field in the ionosphere. These authors have analyzed the seismic sources of various power, in different tectonic structures and at different latitudes. Quasi-static electric fields with the amplitude of the order of 10 mV/m related to the earthquake preparation were found. The horizontal dimension of the perturbed zones was approximately several hundred of kilometers. The location of the electric field bursts coincided with the regions of crossing of the satellite of the perturbed magnetic flux tubes at the altitude of its trajectory. The duration of the electric field perturbation in the ionosphere with amplitude of the order of 10 mV/m may constitute up to 15 days. The perturbation of the electric field in the ionosphere above the regions of typhoon development are described in papers (Isaev et al., 2002; Sorokin et al., 2005a). The characteristic features are similar to those observed above seismic regions. Thus, the satellite data allow us to conclude that the large scale seismic and meteorological events are accompanied by the formation of the perturbation of the quasi-static electric field in the ionosphere with the amplitude of the order of 10 mV/m and duration from a few tens of hours to a few tens of days.

The *in situ* observations of quasi-static electric field in the ionosphere agree with results of numerical simulations of the ionosphere perturbations that arise prior to earthquakes (Zolotov et al., 2008; Klimenko et al., 2011; Namgaladze et al., 2009). In addition the spatial distribution of total electron content (TEC) with the help of GPS receivers was also analyzed. In these papers the global model of the upper atmosphere was used. The latter describes thermosphere, ionosphere and plasmasphere as the unified system. The background electric field is supplemented by small perturbation of the electric field which leads to the perturbation of the first emission layer (FEL) which corresponds to the observed perturbation in the region of earthquake preparation. The numerical simulation showed that the amplitude of the electric field perturbation that is necessary for appearance of the observed FEL constitutes (3–9) mV/m.

Observations of the electric field on the Earth's surface in seismic regions were carried out in the papers (Jianguo, 1989; Nikiforova and Michnowski, 1995; Vershinin et al., 1999; Hao et al., 2000; Rulenko, 2000). The data analysis showed that during earthquake preparation there is an evidence of appearance of short with the duration from a few units to a few tens of minutes local bursts of the high amplitude electric field which amounts for a few kV/m. However, explicit perturbations that exceed the background values and duration of a few days and observed simultaneously at horizontal distances of a few tens and a few hundreds of kilometers were not observed.

The sources of seismic related quasi-static electric fields can be located in the lithosphere, in the atmosphere and in the boundary layer between the lithosphere and atmosphere. Kim and Hegai (1999), Denisenko et al. (2008) and Ampferer et al. (2010) have assumed that the EMF is located in the lithosphere, and the field is transferred through the atmospheric layer with specified altitude dependent electric conductivity. The electric field in the ionosphere was calculated at given spatial distributions of its vertical component on the Earth surface. Calculations carried out in these works show that at the maximal field value on the Earth's surface the electric field in the ionosphere can reach not more than 3–10 mV/m obtained from experiments. Therefore, we can conclude that these models are not able to explain the generation of seismic-related DC electric field in the ionosphere with magnitude up to 10 mV/m and horizontal spatial scale 100–1000 km, which arises during several days in the ionosphere. The detailed analysis of generation of the electric field in the ionosphere before earthquakes is presented in the review of Sorokin and Hayakawa (2013).

For the first time interpretation of observations of quasi-static electric field in the ionosphere and on the ground in seismic region has been given in the framework of electrodynamics of atmosphere–ionosphere interaction in the papers (Sorokin et al., 2001; Sorokin et al., 2005b; Sorokin et al., 2007; Sorokin and Chmyrev, 2010; Sorokin and Hayakawa, 2013 and references therein). According to this model the growth of the electric field in the ionosphere is stipulated by the amplification of the electric current at the area of the global atmosphere–ionosphere electric circuit. The appearance of the electric current is due to the formation of an EMF and variation of the electrophysical characteristics of the lower atmosphere as the result of the intense emission of the charged aerosols by soil gases and their vertical convective transport in the atmosphere. In the framework of this model it was found a mechanism of amplification with the height of the conductive electric current flowing in the layer the earth-ionosphere and mechanism of saturation of the vertical component of the field on the ground level. Mechanism of the amplification of conductive electric current is connected with the conservation of the total electric current. The latter consists of two parts, the external conductive current due to an EMF and conductive electric current. Thus, the decrease with height of external current leads to the corresponding decrease of the conductive electric current. Thus, in this case even if conductivity increases with the height the electric field may attain the value of 10 mV/m. The saturation of the electric field at the ground level is connected with the feedback between external current due an EMF and generated by this current electric field. Estimations showed that the value of the perturbation on the ground level does not exceed the background level.

The perturbation of the electric current at the area of the global circuit above the seimo-active region leads to the modification of the E-layer (Sorokin et al., 2006). These authors developed the method for the calculation of distribution of the electron concentration in the lower ionosphere arising due to an EMF at the ground level of the

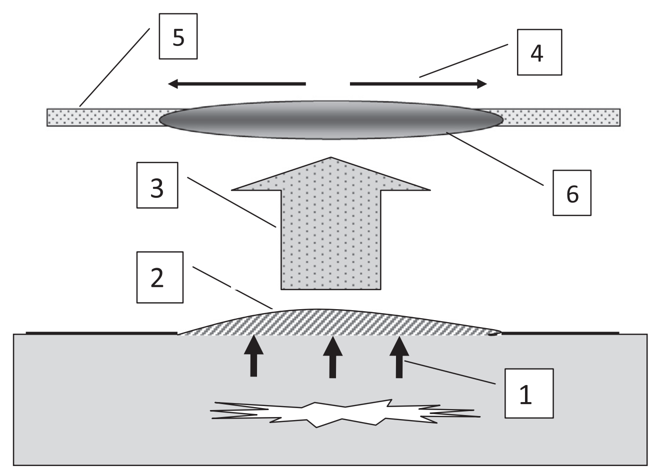

Fig. 1. Scheme of formation of the inhomogeneity in the lower ionosphere caused by perturbation of the electric current in the global circuit in the epicentral zone. 1. Injection of the charged aerosols by the soil gazes. 2. The region of the convective transport of the charged aerosols and formation of the EMF. 3. Perturbation of the conductive electric current. 4. Electric current in the ionosphere. 5. Ionospheric conductive layer. 6. Plasma inhomogeneity in the lower ionosphere.

atmosphere. The scheme of formation of inhomogeneity in the lower ionosphere is depicted in Fig. 1. It is shown that amplification of the electron current flowing between the earth and the ionosphere leads to the increase of plasma density in the E-layer. The reason for that is due to the fact that electric current carries upwards positively charged ions from the atmosphere. This charge is compensated by the electrons of the field-aligned current and by the negatively charged ions from the lower ionosphere. As the result in the lower ionosphere appears horizontally elongated inhomogeneity which affects the amplitude and phase of the radio waves propagating in the earth-ionosphere waveguide. Let us introduce the Cartesian system of coordinates with the z axis directed vertically upwards and with the origin at the earth's surface. We denote $r = \sqrt{x^2 + y^2}$. The plane $z = z_1$ coincides with the lower boundary of the ionosphere. The spatial distribution of the electron concentration $N(r, z)$, the Pedersen conductivity $\sigma_P(r, z)$ and the radial component of the electric field $E(r)$ arising as the result of flowing of axially symmetric perturbation of the electric current from the atmosphere into the ionosphere is defined by the system of nonlinear equations:

$$e\beta[N_0^2(z) - N^2(r,z)] = \left\{E(r)\frac{\partial\sigma_P(r,z)}{\partial r} + \sigma_P(r,z)\left[\frac{dE(r)}{dr} + \frac{E(r)}{r}\right]\right\}$$

$$E(r)\int_{z_1}^{\infty} dz\sigma_P(r,z) = \frac{1}{2r}\int_0^r r' j_1(r')dr';$$

$$\sigma_P(r,z) = \frac{e}{B}\frac{\omega_i \nu_{in}(z)}{\omega_i^2 + \nu_{in}^2(z)}N(r,z),$$

where $N_0(z)$ is the altitude profile of the electron concentration in the unperturbed ionosphere, ω_i, ν_{in} are the ion gyrofrequency and the ion-molecule collision frequency, respectively, e is the electron charge, β is the recombination coefficient, B is the induction of the geomagnetic field and $j_1(r)$ is conductive electron current at the lower ionosphere boundary. The example of calculation of the spatial electron distribution with the use of this system of equations is depicted in the Fig. 2. The results of calculations show that the atmospheric electric current flowing into the ionosphere leads to formation of the layer of electron number density in the lower ionosphere. The electron concentration in the maximum of the E-layer increases by an order in value. The horizontal spatial scale is of the same order as the scale of EMF in the epicentral zone. The horizontal scale of the exterior EMF current in near ground atmosphere is of the order of 100 km. The appearance of the additional electric field in the ionosphere results in oscillations of the lower ionosphere the spectrum of which possesses maximums.

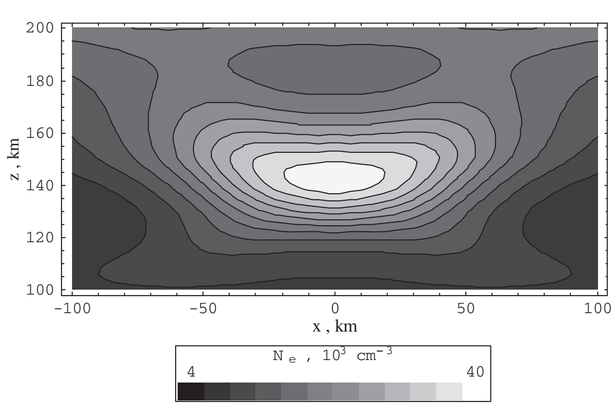

Fig. 2. Results of the calculations of the electron density spatial distribution in the plasma inhomogeneity of the lower ionosphere.

3. Formation of maximums in the ionosphere oscillation spectrum

Recently Sorokin and Pokhotelov (2010) have been studied the influence of the geomagnetic field **B** on the motion of conductive ionosphere plasma under the action of the wind. This influence is due to the Ampere's force, which arises in the conductive layer in the lower ionosphere. The Ampere's force **F** is defined by the flowing in this layer electric current **j** according:

$$\mathbf{F} = [\mathbf{j} \times \mathbf{B}]. \quad (1)$$

The generation of the electric current **j** is stipulated by the motion of the ionosphere plasma moving with the velocity **V** in the geomagnetic field. The existence of geomagnetic field leads to the appearance of the Ampere's force, the vertical gradient of which modifies the features of the internal gravity force. Propagation of the background IGWs upwards is accompanied by the atmosphere perturbations with the following characteristics. A discrete spectrum of ionosphere perturbations appears with certain periods.

In order to simplify the analysis of the consideration of the influence of the wind on the IGWs Sorokin and Pokhotelov (2010) considered the horizontal plasma transport in the vertical magnetic field. The latter assumes that the electric field **E**, generated during plasma movement is orthogonal to the geomagnetic field. The wind velocity **V** and plasma parameters are assumed to be uniform in the horizontal plane. Since the system is quasi-stationary then the condition $\nabla \times \mathrm{E} = 0$ yields. The latter assumes that the $\mathbf{E} = const$ along the altitude. From the condition $\mathbf{E}(z \to \infty) = 0$ follows that the electric field equals zero and one can neglect this value. Sorokin and Pokhotelov (2010) derived the equation for propagation of IGWs in the presence of the horizontal wind:

$$\omega^2\left(\Delta + \frac{1}{H}\frac{\partial}{\partial z}\right)p - \omega_g^2\left(\Delta - \frac{\partial^2}{\partial z^2}\right)p + \frac{\Omega^2}{F}(\mathbf{F}\cdot\nabla)\frac{\partial p}{\partial z} = 0;$$

$$\Omega^2(z) = \frac{1}{\rho}\frac{dF(z)}{dz}, \quad (2)$$

where p is the perturbation of the pressure in the wave, H is the vertical scale of the inhomogeneous atmosphere, $\omega_g = \sqrt{(\gamma - 1)g/\gamma H}$ is the height-averaged Brunt-Vaisala frequency, g is the gravitational acceleration, γ is the ratio of specific heats, ρ is the mass density of the atmosphere. We introduced the Cartesian system of references (x, y, z) with the z-axis directed vertically upwards along the uniform geomagnetic field as it is shown in Fig. 3. Connected with the wind peculiarities of IGW propagation are defined by the vertical gradient of the Ampere's force Ω^2. When $\Omega^2 = 0$ this equation reduces to the classical equation for IGW in the atmosphere at rest.

As it was shown in the papers (Sorokin et al., 2005b; Sorokin et al., 2007; Sorokin and Chmyrev, 2010) in the ionosphere above the seismic region there arises the quasi-static electric field during earthquake preparation which attains the value of the order of 10 mV/m. In the case of simultaneous action of the wind and electric field from the seismic source the electric current is defined by the expression:

$$\mathbf{j} = \hat{\sigma}(\mathbf{E} + \mathbf{V} \times \mathbf{B}),$$

where $\bar{\sigma}$ is the ionosphere conductivity tensor, the components of which are: σ_P is Pedersen conductivity and σ_H is Hall conductivity. Substituting this expression into Eq. (1) one finds:

$$F_x = B_z[\sigma_P(E_y - B_z V_x) - \sigma_H(E_x + B_z V_y)]$$

$$F_y = -B_z[\sigma_P(E_x + B_z V_y) + \sigma_H(E_y - B_z V_x)]$$

Let us consider the wave propagation in the plane (x, z). The wave vector $\mathbf{k}$ also localized in this plane and thus the wave parameters are independent from the coordinate y. From Eq. (2) follows that the Ampere's force in the ionosphere does not influence the wave propagation in the direction perpendicular to the action of the force $(\mathbf{F}_0 \cdot \nabla) = 0$. In other words only the component of the Ampere's force that lies in the plane of the wave propagation influences the wave propagation in the ionosphere. We consider that the velocity of wind is directed opposite to the direction of the y-axis and external electric field is opposite to the x-axis, as it is shown in Fig. 3. Thus we have $E_x = -E$, $V_y = -V$, $B_z = B$, $F_x = F$. The value of the component of the force in the plane of the wave propagation is defined by

$$F = B\sigma_H(E + BV). \quad (3)$$

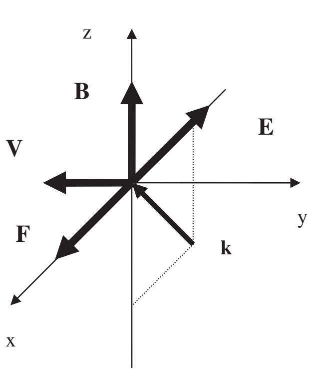

Fig. 3. The system of coordinates.

The altitudinal profile of $\Omega^2(z)$ in Eq. (2) shows that the influence of the Ampere's force (3) is mainly concentrated in the range of the altitudes of lower ionosphere. The layer with nonzero Ampere's force reduces to the boundary between upper and lower semi-spaces where the waves unaffected by this force. We suppose that the wave pressure depends on the coordinate x according to $p \approx \exp(ikx)$. The influence of this force on the propagation of IGWs is described by the boundary conditions (Sorokin and Pokhotelov, 2010):

$$p_+ = p_-; \quad \frac{dp_+}{dz} = \frac{dp_-}{dz}\exp\left(\frac{ik\eta}{\omega^2}\right); \quad \eta = \int_{-\infty}^{\infty}\frac{dz}{\rho}\frac{dF}{dz}. \quad (4)$$

Here $\pm$ signs denote the values above and below the layer, where the Ampere's force is nonzero. The first condition denotes the continuity of the pressure at the layer. The second one denotes the phase shift of the derivative by the value $k\eta/\omega^2$. Influence of the layer is described by the integral factor η. Outside the layer the perturbation of the pressure in IGW yields Eq. (2) with $\Omega^2 = 0$. Its solution has the form in the semi-space above the layer $p = c_1\exp(\kappa_1 z)$ and in the semi-space below the layer $p = c_2\exp(\kappa_2 z)$, where:

$$\kappa_{1,2} = -\frac{1}{2H} \pm \sqrt{\frac{1}{4H^2} + k^2\left(1 - \frac{\omega_g^2}{\omega^2}\right)}.$$

Substituting the expressions for the pressure in IGWs into the boundary condition (4), one finds:

$$\kappa_1 = \kappa_2\exp(ik\eta/\omega^2).$$

In particular case

$$k\eta/\omega^2 = 2\pi n; \quad n = 1, 2, 3, \ldots \quad (5)$$

one obtains the condition $\kappa_1 = \kappa_2$, from which one finds the dispersion relation for IGWs

$$k^2 = \frac{\omega^2}{4H^2(\omega_g^2 - \omega^2)}. \quad (6)$$

Excluding k from (5) and (6) one obtains the discrete spectrum of frequencies ω_n:

$$\omega_n^2(\omega_g^2 - \omega_n^2) = \left(\frac{\eta}{4\pi H}\right)^2\frac{1}{n^2}. \quad (7)$$

According to the boundary conditions (4) and (5), the pressure and its normal derivative are continuous at the layer where Ampere's force is nonzero. This means that Ampere's force does not influence the wave propagation. However, the influence of the layer with $\Omega^2 \neq 0$ on such waves leads to their scattering. The wave frequency of which do not satisfy equality (5), damp much faster. This means that the IGWs with frequencies yielding Eq. (7) are more preferable. In terms of periods $T_n = 2\pi/\omega_n$ this equation reads:

$$T_n = T_g n\sqrt{1 + \sqrt{1 - \lambda^2/n^2}}. \quad (8)$$

In Eq. (8) we denoted $T_g = 8\pi^2 H\omega_g/\sqrt{2}\eta$; $\lambda = \eta/2\pi H\omega_g^2$. Eq. (8) allows us to calculate the values of periods in the maximums of spectra of ionosphere induced by the passage of IGWs from the atmosphere, the features of which influenced by the Ampere's force localized in the conductive layer.

Let us make some estimations. Substituting (3) into (4), one obtains

$$\eta = B(E + BV)\int_{-\infty}^{\infty}\frac{dz}{\rho}\frac{d\sigma_H}{dz}. \quad (9)$$

In order to estimate η let us represent the altitudinal dependence of ionosphere conductivity in the form

$$P\sigma_H = \frac{9}{2}\sigma_0\left[1 - \exp\left(-\frac{z}{l}\right)\right]\exp\left(-\frac{z}{2l}\right); \quad z > 0$$
$$\sigma_H = 0; \quad z < 0. \quad (10)$$

The origin of the coordinate $z = 0$ is chosen at the lower boundary of the conductive layer. Supposing $\rho = \rho_0\exp(-\frac{z}{H})$ and substituting (10) into (9), one finds

$$\eta = B(E + BV)\frac{\sigma_0}{\rho_0}\frac{18Hl}{(2l - H)(3H - 2l)}.$$

Assuming

$$H = 10\ \text{km}; \quad l = 14\ \text{km}; \quad B = 10^{-4}\ \text{T}; \quad \sigma_0 = 4\times10^{-4}\ \text{S/m}$$

$$\rho_0 = 2\times10^{-9}\ \text{kg/m}^3; \quad \omega_g = 1,7\times10^{-2}\ \text{s}^{-1},$$

one finds

$$\eta = 1.14\times10^3(E + BV). \quad (11)$$

Let the seismic activity is absent and the electric field in the ionosphere is zero, $E = 0$. Suppose the wind velocity in the ionosphere to be $V = 60$ m/s. Then from (11) one finds $\eta = 6.8$ m/s. Substituting this value into (8) one finds the formula for calculation periods in minutes in maximums of ionosphere oscillations during seismically quiet conditions

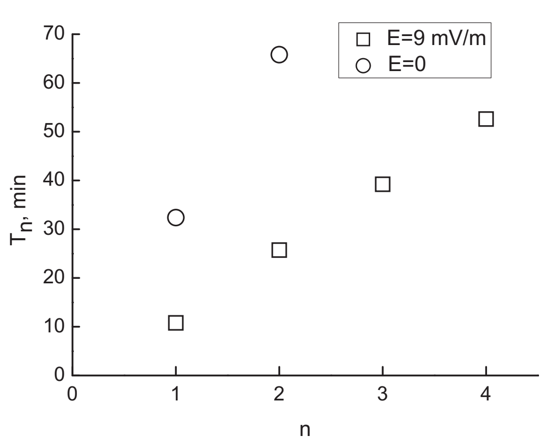

Fig. 4. The values of periods corresponding to spectrum maximums of oscillations in the lower ionosphere. Circles – the electric field is zero, squares – the electric field equals 9 mV/m.

$$T_n = 23.5n\sqrt{1 + \sqrt{1 - 0.14/n^2}}. \quad (12)$$

Let the growth of seismic activity to be accompanied by the appearance of additional quasi-static field of the value $E = 9$ mV/m. From (11) one finds $\eta = 17$ m/s^2. Substituting this value in (8) one finds the formula for the calculation periods in minutes for the maximums in spectrum of ionosphere oscillations during the growth of seismic activity.

$$T_n = 9.4n\sqrt{1 + \sqrt{1 - 0.88/n^2}}. \quad (13)$$

Fig. 4 shows the dependence of periods T_n on the number of spectral line calculated with the help of (12) и (13). One sees that during quiet conditions the value of the main maximum corresponding to $n = 1$, constitutes approximately 30 min. This corresponds to meso-scale oscillations which regularly observed during the quiet conditions. They can arise due to the wind in the ionosphere which influences the background IGWs the sources of which are in the atmosphere. During preparation of the earthquakes there is an additional electric field. Connected with it the Ampere's force modifies the spectrum of oscilations in a way that appear short periods of the order 10 and 25 min. The fact of appearance of discrete spectrum is connected with the existence of the transition layer in which $\Omega^2 \neq 0$.

4. Conclusions

It was shown that the increase of seismic activity is accompanied by amplification of quasi-static electric field up to the value of the order of 10 mV/m. This increase is connected with the perturbation of the electric current in the region of the global circuit in the vicinity of seismic zone. The cause for such perturbation is an EMF in the near ground atmosphere that appears as the result of injection of charged aerosols and their convective upward transport. The electric conductivity current flowing from the atmosphere to the ionosphere carries there the positively charged ions. This positive charge is compensated by the electrons from the field aligned electric current and by negatively charged ions from the lower ionosphere. As the result at the lower boundary of the ionosphere there forms elongated inhomogeneity of plasma density. The existence of such inhomogeneity leads to the appearance of perturbation of the amplitude and phase in the course of waveguide propagation of VLF/LF signals in the epicentral zone during earthquake preparation.

Moreover, it was shown that observed oscillations of the ionosphere are connected with the background IGWs propagating from the lower atmosphere up to ionosphere heights. The analysis of the averaged spectra of background perturbations showed the existence of spectral lines. The rule of selection is different from that for resonator since in each moment one can observe the waves with different frequencies. Only being averaged over substantially large time domains one can reveal predominance of the waves with specific frequencies. The interaction of the wind in the ionosphere with geomagnetic field leads to the appearance of the Ampere's force, the vertical gradient of which modifies the features of IGWs. There arises the discrete spectrum of perturbations with the basic period of 30 min. During earthquake preparation in the ionosphere above the epicentral zone appears the quasi-static electric field with the amplitude of 10 mV/m, which increases the Ampere's force, formed by the wind. According to our calculations the wave gas pressure and its normal derivative are continuous for selected periods during propagation across conductive layer, where the Ampere's force operates. This means that the waves with these periods are not affected by this force. The action of the Ampere's force does not provide the arrest on the waves with other periods. However, the influence of this layer on these waves results in their scattering. Therefore, the wave period of which does not satisfy the condition of propagation across the conductive layer. They damp stronger. This leads to predominant growth of the amplitude of the perturbations with discrete spectrum, period of which satisfies such a condition. The increase of the Ampere's force due to the electric field of seismic origin results in the appearance in the spectrum of ionosphere oscillations of maximums with short periods of the order 10 and 22 min. They are really observed in the experiments.

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