This article is devoted to the brilliant memory of Professor Mykola Kotsarenko (02.10.1941 – 09.02.1998)

ACOUSTIC CHANNEL OF THE LITHOSPHERE-IONOSPHERE COUPLING

S.V.KOSHEVAYA, V.V.GRIMALSKY[1], G.N.BURLAK, A.N.KOTSARENKO[2]

Autonomous University of Morelos
(II •, Av. Universidad, Z.P.62210 Cuernavaca, Morelos.Mexico; e-mail:svetlana@uaem.mx),
[1]Instituto Nacional de Astrofisica, Optica y Electronica (INAOE)
(B.O.Box 51,216, Z.P.72000, Puebla, Mexico),
[2]Institute of Geophysics
(UNAM, Campus Juriquilla, Queretaro, Qro., Mexico)

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The acoustic channel of the litosphere-ionosphere coupling is demonstrated by examples a few phenomena like the exciting of magnetic perturbations of fields and the 'swinging“ of E- and F-layers. The results can be used in ground and space experiments on a research of electromagnetic processes in the ionosphere, caused by volcano and seismic activities and the warning of these natural phenomena.

Introduction

Now there are a lot of experimental observations [1 – 5] demonstrated the passing of the energy of natural hazards (seismic and volcano activities, tzunami, tornado, typhoon) from the lithosphere into the ionosphere. The connection of the physical phenomena occurring in the lithosphere-atmosphere-ionosphere now does not cause doubt, and actual is only the creation of its consecutive theory. Especially important are these questions in connection with an opportunity of creation of a global space-ground monitoring system for earthquakes. It should be noted that the consecutive theory of the lithosphere-ionosphere coupling is not developed yet to the present time. The mechanisms of interaction of the specified environments of the Earth are not absolutely clear. Though, in our opinion, it is necessary to allocate three basic channels of the lithosphere-atmosphere-ionosphere coupling: electromagnetic, acoustic, and geochemical ones [6 – 9].

The acoustic channel of the lithosphere-ionosphere coupling [7, 8], which is carried out by means of atmospheric acoustic waves raised by fluctuations of a terrestrial surface, is rather efficient due to several factors. First, atmospheric waves have one extremely remarkable property: their amplitude accrues with height by the exponential law. Whereas the density of neutral gas falls down with height by the Boltzmann's law $N(z) \approx N_0 e^{-\frac{z}{H}}$, where H is the height of a homogeneous atmosphere $H = k_b T / mg$, and the flow of energy of an acoustic wave remains constant $N(z) |V_{\tilde{u}}|^2 = \mathrm{const}$, the amplitude of speed of an acoustic wave is about the speed of sound of 104 – 105 cm/s. Taking into account that the dispersion law for vertically extending atmospheric acoustic waves looks like

$$\Omega^2 = \Omega_a^2 + k^2 s^2, \qquad (1)$$

where $\Omega_a = s/2H$ is the cut-off frequency, $s = \sqrt{\gamma P_0/\rho_0}$ is the speed of sound, and that the attenuation of waves caused by viscosity strongly grows with increase of frequency (as $\sim \Omega^2$), it is possible to expect that the effect of increase of atmospheric acoustic waves, which is essential only at frequencies Ω close to frequency $\Omega_a \sim 10^{-2}\ 1/s$, will be real. The supervision confirms this conclusion [1 – 5]. The following factor ensuring the efficiency of the lithosphere-ionosphere coupling, consists in the available mechanism of interaction of acoustic and plasma waves in the ionosphere by means of collisions of neutral particles with ions. In the ionosphere with weakly ionized plasma, the prevailing role is played by collisions of ions with neutral particles. Below, we shall demonstrate the acoustic channel by a few examples like the exciting of magnetic perturbations, and 'swinging“ the E- and F- of layers of the ionosphere in the field of a seismic wave.

Excitation of Magnetic Perturbations by Seismic Waves

Below, the description of the acoustic channel of the lithosphere-ionosphere coupling uses the model of magnetized plasma. The magnetostatic field of the Earth is given as $\vec{B}_0 = B_0 (\sin\theta, 0, \cos\theta)$, where θ is the angle between the magnetic field and the direction of a vertically propagating wave $0Z$. The transformation of atmospheric acoustic waves into Alfven waves exciting the magnetic perturbations is investigated by using the Maxwell's equations:

$$a)\ \mathrm{rot}\,\vec{B} = \frac{4\pi}{c}\vec{j},\quad b)\ \vec{j} \equiv e(n_i\vec{V}_i - n_e\vec{V}_e) = \hat{\sigma}\vec{E} + \vec{j}_{\mathrm{ext}},$$

$$c)\ \mathrm{rot}\,\vec{E} = -\frac{1}{c}\frac{\partial\vec{B}}{\partial t}. \qquad (2)$$

In the linear approximation, $n_i = n_e = n_{i0}$. The tensor of conductivity $\hat{\sigma}(\omega)$ and $\vec{j}_{\mathrm{ext}}$ have been determined from the equations of motion for electrons and ions:

$$\frac{\partial\vec{V}_e}{\partial t} = -\frac{e}{m_e}\vec{E} - \vec{V}_e \times \vec{\omega}_{He} - \nu_e(\vec{V}_e - \vec{V}_n), \qquad (3)$$

$$\frac{\partial\vec{V}_i}{\partial t} = -\frac{e}{m_i}\vec{E} - \vec{V}_i \times \vec{\omega}_{Hi} - \nu_i(\vec{V}_i - \vec{V}_n). \qquad (4)$$

In (3), and (4), the frequencies $\omega_{He,i} = eB/m_{e,i}c$ are the cyclotron waves of electrons and ions; ν_e and ν_i are the collision frequencies of electrons and ions with neutral particles and ions. The system of equations (3), (4) is complemented with other equations. First, it is necessary to use the equation for neutral particles:

$$\rho\frac{\partial\vec{V}_n}{\partial t} = -\nabla P + \eta\Delta\vec{V}_n + \rho\vec{g} - \rho\nu_n(\vec{V}_n - \vec{V}_i). \qquad (5)$$

In (5), P is the pressure of the neutral gas, ν_n is the frequency of collisions of molecules with ions; ρ, η, and g are the gas density, dynamic viscosity, and the gravitational acceleration, respectively.

It is possible from Eqs. (2) – (5) to find

$$\vec{J}_{\mathrm{ext}} \approx \frac{\omega_{pe}^2 m_e}{4\pi e}\left[\left(\frac{\nu_i^2}{\nu_i^2+\omega_{Hi}^2} - \frac{\nu_e^2}{\nu_e^2+\omega_{He}^2}\right)\vec{V}_{n\perp} + \right.$$

$$\left. + \left(\frac{\omega_{Hi}\nu_i}{\nu_i^2+\omega_{Hi}^2} - \frac{\omega_{He}\nu_e}{\nu_e^2+\omega_{He}^2}\right)\left[\vec{V}_{n\perp}\times\frac{\vec{B}_0}{B_0}\right]\right], \qquad (6)$$

where $\omega_{pe}^c = (4\pi e^2 n_e/m_e)^{1/2}$ is the Langmuir frequency of electrons and $\vec{V}_{n\perp}$ is the velocity of neutral particles perpendicularly to the magnetic field (the inclination used below is $\theta = 30°$). Our calculations show that the maximum induced current at frequencies $0.1 - 1\ \mathrm{s}^{-1}$ is achieved at heights 150 – 200 km, see

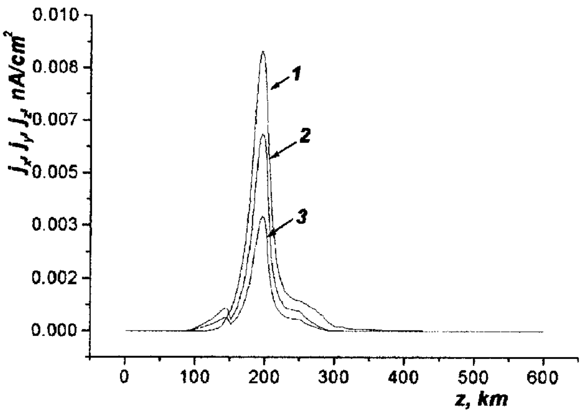

Fig. 1. Dependences of the components of the induced current j_x, j_y, j_z (curves *1*, *2*, *3*, respectively) on the vertical distance z. The frequency of the initial acoustic wave is $\omega = 0.1\ \mathrm{s}^{-1}$ and the amplitude of the velocity at $z = 0$ is $V_{z0} = 1$ cm/s

Fig.1. Here, the vertical distribution of the components of the density of induced current is given for frequencies $\omega = 0.1\ \mathrm{s}^{-1}$ and $\omega = 1\ \mathrm{s}^{-1}$, respectively. Finally, the air motion amplitude at the Earth's surface is $V_{z0} = 1$ cm/s around the sound speed.

Using the expressions for the external current, one can calculate all alternative electromagnetic field components, where only variations along the $0Z$ axis are considered. The Fourier transforms for the X and Y coordinates are obtained, and the Maxwell's equations are reduced to a set of two second-order equations for the tangential components of the electric field $E_{x,y}$ with boundary conditions at z = 0 (the Earth's surface) and z = 600 km (magnetosphere). The Earth's surface is assumed as ideally conductive, i.e., $E_{x,y} = 0$. The radiation conditions have been used in the magnetosphere. Namely, it has been assumed that two outgoing waves have been presented in the magnetosphere. Those waves are Alfven and fast magnetosonic waves.

Using the assumptions for Alfven waves ($\omega \approx \omega_{Hi}$, $ck \approx \omega_{pe}$, where ω_{pe} is the Langmuir frequency of electrons) and neglecting the terms $\nu_i\nu_e$ in comparison with ω^2, we obtain a dispersion relation in the form:

$$k \approx \frac{\omega}{C_A}\left(1 + \frac{i\nu_e}{2\omega_{He}}\right), \qquad (7)$$

where $C_A = B_0/(4\pi n_{0i} m_i)^{1/2}$ is the Alfven speed. An Alfven wave can be excited by an atmospheric sound wave, when the frequency of the acoustic wave is greater than the cut-off frequency $\Omega_0 = Cs/2H$, and the acoustic wave penetrates into the ionospheric E-layer. This gives the actual frequency range

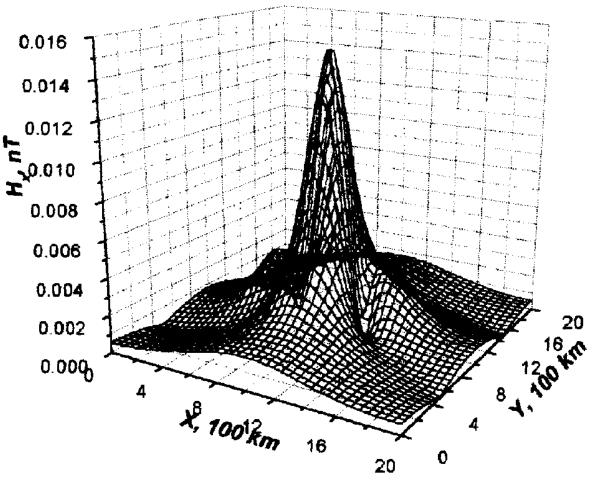

Fig. 2. Distribution of the H_x component of the magnetic field at the Earth's surface, i.e., $z = 0$ for $\omega = 0.1\ s^{-1}$

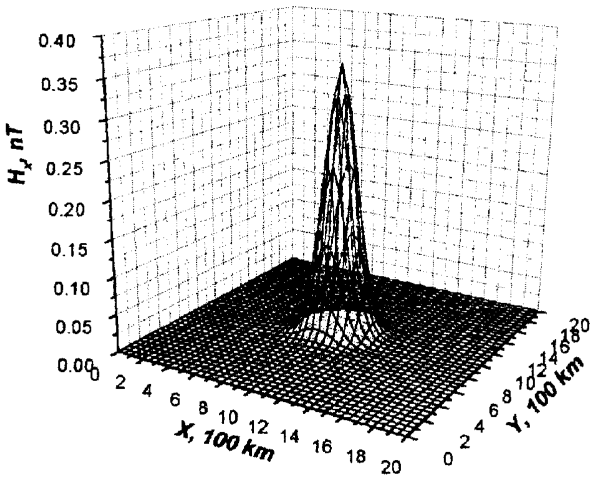

Fig. 4. Distribution of the H_x component of the magnetic field at z = 200 km, for $\omega = 0.1\ s^{-1}$

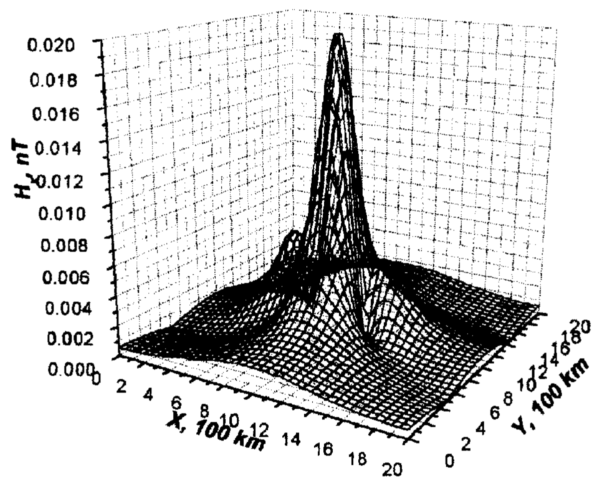

Fig. 3. Distribution of the H_x component of the magnetic field at z = 100 km, for $\omega = 0.1\ s^{-1}$

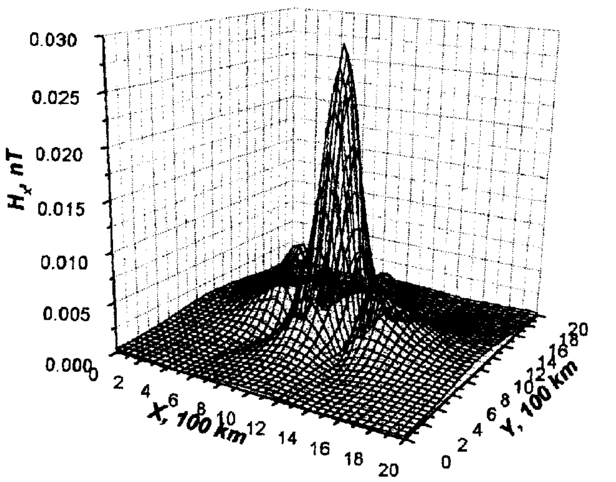

Fig. 5. Distribution of the H_x component of the magnetic field at z = 400 km, for $\omega = 0.1\ s^{-1}$

$0.025 < \omega < 10\ s^{-1}$. The main emphasis in our model calculations has been directed into the possible magnitudes of the alternating magnetic fields excited by ultra-low-frequency acoustic waves moving vertically upwards. The maximum amplitude of the velocity of particles in the acoustic wave at the Earth surface is $V_{z0} = 1$ cm/s. The transverse distribution of the profile of the sound amplitude is bell-like with characteristic scales of 100 km in the X and Y directions. The results of numerical simulations are presented in Figs. 2 – 5 where the transverse distributions of the H_x component of the magnetic field are given for different heights z. Other components $(H_{y,z})$ of the excited magnetic field are of the same order of magnitude.

From Figs. 2 – 5, one can see that the maximum values of excited magnetic fields are achieved at the top of the E-layer $z \approx 200$ km. They are about 1 nT at $\omega = 0.1\ s^{-1}$, and 10^{-4} nT at $\omega = 1\ s^{-1}$. Therefore, the acoustic mechanism of excitation of magnetic fields can be essential for the ionospheric observations. But the values of the magnetic fields at the Earth's surface are much smaller. At the frequencies $\omega = 0.1\ s^{-1}$ and $1\ s^{-1}$, the maximal value of H_x component is about 0.01 nT, and 10^{-4} nT, respectively. Thus, the observed variations of the ULF magnetic fields at the Earth surface before the earthquakes are probably caused by other mechanisms.

'Swinging“ of the Ionosphere Layer in a Field of Atmospheric Wave

'Swinging“ of the ionosphere layer in the field of atmospheric acoustic waves excited as a result of earthquakes, is convincingly described in [10]. This phenomenon consists in the following. During the earthquake on Kuril Islands on August 11, 1969 (at 21.27 IT), the surface acoustic Rayleigh’s wave excited during the main peak of the earthquake spread the distance of 5540 km across the Pacific ocean and reached Honolulu, Hawaii (at 21.49 IT), where it was registered by seismic stations. After approximately 8 minutes after the arrival of a Rayleigh’s wave, the scientific radiolaboratory of the University of Hawaii begins to accept Dopplerogramma from the ionosphere station working at a frequency of 5 MHz, that answers the height of reflection $h = 150$ km. Let’s recall that the reflection of a radiowave from an ionosphere layer occurs at the point of equality of Langmuir’s frequency $\omega_p(h)$ to the frequency of a radiowave $\omega = \omega_p(h)$. If the layer makes oscillatory movement with speed $V = V_a \sin \Omega t$, the frequency of a reflected wave due to the Doppler’s effect is equal to

$$\omega' = \omega + \Delta\omega, \qquad \Delta\omega = \omega \frac{V_a}{c} \sin \Omega t. \tag{8}$$

For $\omega \sim 3 \cdot 10^7$ 1/s and $V_a \sim 10^4$ cm/s, the change of the frequency is equal to $\Delta\omega \approx 10$ 1/s. In [10], we can see seismograms and Doppler records have the difference in time $\tau = 8$ minutes answering the time $\tau = h/s$ of the propagation of an acoustic wave from the surface of the Earth up to the point of reflection of a radiowave, that testifies to the acoustic channel of influence of the lithosphere on the ionosphere.

To study the 'swinging“ of an ionosphere layer in the field of an atmospheric acoustic wave, we take the advantage Chapmann’s function determining the speed of formation of electrons and ions due to the ionization of a neutral gas by solar radiation:

$$q(z, \chi) = q_{e\,\max}(\chi) \exp\left\{1 - \frac{z - z_m}{H} - e^{-\frac{z - z_m}{H}}\right\}. \tag{9}$$

Here, $q_{e\,\max}(\chi)$ is the maximum of the function $q(z, \chi)$, z_m is the coordinate of the maximum of the speed of formation of electrons (and, simultaneously, the coordinate of the maximum of the density of ionosphere plasma):

$$z_m = H \ln(\tau \sec \chi), \tag{10}$$

χ is the zenith angle, $\tau = N_0 Q H$ is the optical thickness, Q is the cross-section of absorption of solar radiation by a neutral particle. The high-altitude distribution of the electronic density $n_e(z)$ is received by equating $q_e(z, t)$ to the parameter αn_e^2 of the recombination speed, so $n_e(z) = \sqrt{q_e(z, \chi)/\alpha}$ ($q_e(z, \chi) = \beta n_e$ in the case of so-called β-Chapmann’s layer, when the main role is played by processes of sticking of electrons to neutral molecules). At the presence of an acoustic wave, the complete density of neutral particles is

$$N(z) = N_0 e^{-\frac{z}{H}} + \delta N(z, t) = n_0(z)\{1 + \delta N(z, t)/n_0(z)\} \tag{11}$$

where $n_0(z) = N_0 e^{-\frac{z}{H}}$, $\delta N(z, t)$ is the additive to the density of neutral gas caused by an acoustic wave. For $\lambda \ll H$, where $\lambda = 2\pi s/\Omega$ is the lenght of an acoustic wave, we find $\delta N(z, t)$ from the equation of continuity, including the parametric dependence n_0 on z:

$$\frac{\partial}{\partial t}\delta N + \frac{\partial}{\partial z} n_0 V = 0.$$

Then we obtain

$$\delta N(z, t)/n_0 = \frac{V_a(z)}{s}\cos(\Omega t - kz) =$$

$$= \frac{V_a(0)}{s} e^{\frac{z}{2H}} \cos(\Omega t - kz). \tag{12}$$

Replacing N_0 by $N_0(1 + \delta N/n_0)$ in (10) according (11), (12) and considering $\delta N/n_0 \ll 1$, we find the coordinate of the maximum density of ionosphere plasma z_m:

$$z_m = z_{m0} + \delta z_m(z, t) = z_{m0} +$$

$$+ H \frac{V_a(0)}{s} e^{\frac{z_{m0}}{2H}} \cos\left(\Omega t - \frac{\Omega}{s} z_{m0}\right), \tag{13}$$

where the coordinate of the maximum density z_{m0} of ionosphere plasma in the absence of a atmospheric acoustic wave is defined by (13). Formula (13) received in the linear approximation suits the case $\frac{V_a(0)}{s} e^{\frac{z_{m0}}{2H}} \ll 1$. Nevertheless, the upper estimation for the size $|\delta z_m|$ can be received according $\frac{V_a(0)}{s} e^{\frac{z_{m0}}{2H}} \approx 1$. Then the value $|\delta z_m|$ appears to be about the height of a homogeneous atmosphere $|\delta z_m| \approx H$. From (13), it is also possible to receive the value of Doppler's shift of the frequency:

$$\Delta\,\omega = \frac{\omega}{c}\frac{\partial}{\partial t}\delta z_m = \omega\frac{\Omega\,HV_a(0)}{s}\,e^{\frac{z_{m0}}{2H}}\sin\left(\Omega t - \frac{\Omega}{s}z_{m0}\right). \tag{14}$$

Using a reasonable value $\frac{V_a(0)}{s}e^{\frac{z_{m0}}{2H}} \approx 0.03$ and parameters [10] $\omega = 3\cdot 10^7\,\mathrm{s}^{-1}$, $\Omega \approx 0.3\,\mathrm{s}^{-1}$, $H \approx 5$ km, we receive $\omega \approx 5\,\mathrm{s}^{-1}$ that is close to the observable value $f \approx 1$ Hz.

Conclusions

From a wide circle of the questions on the lithosphere-ionosphere coupling, we have analyzed two very interesting effects: the magnetic perturbations caused by seismic waves and the 'swinging" of ionosphere layers by an atmospheric acoustic wave raised by fluctuations of the terrestrial surface. All these effects have the experimental confirmation [1 – 5, 10].

More interesting and experimentally observed is the 'swinging" of the E- and F-layers by an acoustic wave. The amplitude of 'swinging" is determined by the frequency of an acoustic wave and its amplitude of speed. From a wide spectrum of acoustic waves caused by earthquakes, waves with a period of about several tens of seconds reach the ionosphere heights, i.e., only waves with frequencies close to the cut-off frequency of an acoustic wave reach the ionosphere. The unknown size for estimations is the amplitude of speed of an acoustic wave at the ionosphere heights. Due to the exponential increase, the amplitude of the speed of a wave, being about mm/s at the terrestrial surface, exceeds the speed of sound at the ionosphere heights. It is clear that a nonlinear restriction of the amplitude of speed will take place, which is founded in the framework of the especially nonlinear theory of atmospheric acoustic waves. In addition, the speed of sound can depend on the amplitude of a wave, as it takes place, for example, in soliton-like nonlinear waves [11]. Was observed in a number of experiments, where acoustic shock waves caused by a Rayleigh's wave at the surface of the Earth during an earthquake were registered at heights of about 300 km in a time of 15 s. Hence, the speed of acoustic fluctuations in the atmosphere is about $2\cdot 10^6$ cm/s that exceeds many times the speed of a usual sound at the surface of the Earth. According to (13) for this speed, the amplitude of the 'swinging" of an ionosphere layer will exceed the height of a homogeneous atmosphere H. For the amplitude of ' swinging" equal about the value about 20 km, waves with speeds $S \approx 10^5$ cm/s are registered at the height $h \approx 170 \div 190$ km of the ionosphere layer. This value of speed is higher by one order than the speed of sound at the surface of the Earth. Hence, the excitation of plasma waves is real probably under the supersonic movement of acoustic pulses such as soliton-like or shock waves similar to ones registered in [11, 12].

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