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Filtration Properties of the Ionosphere and Magnetosphere for ULF EM Radiation Penetrating from Lithosphere

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1. Introduction. The knowledge of frequency and spatial filtration properties of the "lithosphere-ionosphere-magnetosphere" (LAI) system is important for lithospheric origin electromagnetic (EM) radiation detection and identification with the satellites. Such EM radiation can be excited for the reason of anthropogenic and natural factors. It is necessary to mark a seismo- electromagnetic phenomena among natural factors .

It has been shown in [**?**], that there is an mechanical orientation of microcracks correlation effect and microcurrents synchronization into macrocurrent during the earthquakes preparation period. It has been obtained that macrocurrents with typical sizes $\sim 10 - 100km$ can be excited in the lithosphere on the eve of earthquakes.

First the problem of electromagnetic (EM) waves penetration in the magnetosphere from the lithospheric current source with azimuth symmetry was explored in [**?**]. It has been shown that ring currents effectively generate EM fields in the upper ionosphere and magnetosphere. Also more complicate model of the ULF EM waves penetration in the LAI system was explored in [**?**]. The LAI system was represented as a set of thin homogeneous layers, and the geomagnetic field was considered to be oblique. The studies of dependencies of EM waves amplitude on a different altitudes have shown that waves of frequencies $\sim 1Hz$ effectively penetrate into satellite altitudes ($800km$).

However it is not clear as shape of EM perturbation in the ionosphere ($400-800km$) is compared with shape of current source and their location in the lithosphere. Furthermore, unknown the frequency and spatial filtration properties of LIM give no possibility to obtain the epicentre parameters by EM fields recorded with the satellites.

When ULF waves propagate in the magnetosphere their amplitudes will decrease owing to energy losses on the ionospheric reflection and collisions of particles. However the wave amplitude can increase due to cyclotron instability with captured protons in the radiation belts. In this paper we estimate these two competing mechanisms.

The connection of a spatial distribution of EM fields in the upper ionosphere with allocation of current sources in a lithosphere and frequency filtration properties for ULF waves was investigated.

2. The Model and Basic Equations. Let's use a cartesian coordinat system so that the axis z was directed is perpendicular to the surface of the Earth. We suppose that the permittivity of all medium change only in the $z-$ direction, but in tangential plane (xy), the permittivity of all medium remains constant.

As lithosphere and atmosphere being isotropic spaces, their tensors of permittivity are diagonal. The lithospheric permittivity is $\varepsilon_l = 1 - i4\pi\sigma_l/\omega$, where σ_l is lithosphere conductivity, and the atmospheric permittivity is $\varepsilon_a = 1$. Taking into account inclination of geomagnetic field in the ionosphere $\angle(zH) = \theta$, we rewrite the ionospheric permittivity tensor as

$$\varepsilon_{\alpha\beta} = \left\| \begin{array}{ccc} \varepsilon\cos^2\theta + \eta\sin^2\theta & ig\cos\theta & \sin\theta\cos\theta(\eta-\varepsilon) \\ -ig\cos\theta & \varepsilon & ig\sin\theta \\ \sin\theta\cos\theta(\eta-\varepsilon) & ig\sin\theta & \varepsilon\sin^2\theta + \eta\cos^2\theta \end{array} \right\|, \qquad (1)$$

where ε, g and η are well-known permittivity tensor elements in plasma without inclination of the geomagnetic field.

Starting from the well-known differential equation for electric field

$$\Delta\vec{E} - \nabla\left(\nabla\cdot\vec{E}\right) = \frac{1}{c}\frac{\partial}{\partial t}\left(\frac{1}{c}\frac{\partial(\hat{\varepsilon}\vec{E})}{\partial t} + \frac{4\pi}{c}\vec{J}\right)$$

and taking into account the EM field decomposition on plane waves in plane xy, we obtain the equations for the tangential electric field amplitudes

$$\frac{d}{dz}\left[\frac{\varepsilon_{33}-k_y^2/k_0^2}{\mathcal{D}_0}\frac{dE_x}{dz} + \frac{k_xk_y}{k_0^2\mathcal{D}_0}\frac{dE_y}{dz} + i\frac{k_x}{\mathcal{D}_0}\Upsilon + \frac{4\pi k_x}{\omega\mathcal{D}_0}J_z\right] + i\frac{\varepsilon_{13}}{\mathcal{D}_0}\frac{d}{dz}\left(k_xE_x + k_yE_y\right)$$
$$+\left(k_y^2 + k_0^2\tilde{\varepsilon}_{11}\right)E_x + \left(k_xk_y + k_0^2\tilde{\varepsilon}_{12}\right)E_y + i\frac{4\pi\omega}{c^2}\left(\frac{\varepsilon_{13}}{\mathcal{D}_0}J_z - J_x\right) = 0, \qquad (2)$$
$$\frac{d}{dz}\left[\frac{\varepsilon_{33}-k_x^2/k_0^2}{\mathcal{D}_0}\frac{dE_y}{dz} + \frac{k_xk_y}{k_0^2\mathcal{D}_0}\frac{dE_x}{dz} + i\frac{k_y}{\mathcal{D}_0}\Upsilon + \frac{4\pi k_y}{\omega\mathcal{D}_0}J_z\right] + i\frac{\varepsilon_{13}}{\mathcal{D}_0}\frac{d}{dz}\left(k_xE_x + k_yE_y\right)$$
$$+\left[k_yk_x + k_0^2\tilde{\varepsilon}_{21}\right]E_x + \left(k_x^2 + k_0^2\tilde{\varepsilon}_{22}\right)E_y + i\frac{4\pi\omega}{c^2}\left(\frac{\varepsilon_{13}}{\mathcal{D}_0}J_z - J_y\right) = 0. \qquad (3)$$

Here the following definitions have been employed: $\mathcal{D}_0 = \varepsilon_{33} - (k_x^2 + k_y^2)/k_0^2$, $\tilde{\varepsilon}_{\alpha\beta} = \varepsilon_{\alpha\beta} - \varepsilon_{13}\varepsilon_{3\beta}/\mathcal{D}_0$, $\Upsilon = \varepsilon_{31}E_x + \varepsilon_{32}E_y$, $\varepsilon_{\alpha\beta}$ – the elements of tensor (1).

3. The Boundary Conditions. We suppose, that the region of calculation of equations (2, 3), is restricted by homogeneous half-spaces. In case of a problem on penetration ULF EM radiation into magnetosphere, we put the lower boundary under a source in the lithosphere and the upper boundary at the satellites flight altitude in the ionosphere. The condition $\eta \gg \varepsilon$ is always satisfied in the upper ionosphere, therefore Alfvén (AW) and magnetosonic (MS) waves propagate from upper boundary into magnetospheric half-space. Then the dispersion relation for these waves can be written in the system xyz as $k_{z1} = -k_x\tan\theta + k_0\varepsilon^{1/2}/\cos\theta$ and $k_{z2} = (k_0^2\varepsilon - k_x^2 - k_y^2)^{1/2}$ respectively.

The tangential EM field (E_τ, H_τ) can be expressed in the term of wave amplitudes propagating from upper boundary $E_\tau = \hat{\gamma}\vec{C}\exp[-ik_{z1,z2}(z-h_z)]$, $H_\tau = \hat{\rho}\vec{C}\exp[-ik_{z1,z2}(z-h_z)]$. We can derive the elements of a matrix $\hat{\gamma}, \hat{\rho}$ from the Maxwell equations. However in this case, it is easier to derive the boundary condition using relation $E_z = -E_x\tan\theta$, which is caused by great conductivity along a geomagnetic field in the ionosphere. Found from equation (2, 3) the components of matrix $\hat{\gamma}$ and substituted $\vec{C} = \hat{\gamma}^{-1}\vec{E}_\tau$ into the $x-$ and $y-$ projection of $rot\vec{E} = -ik_o\vec{H}$ we find the components of $\hat{\rho}$. Now we can take following expression $\vec{H}_\tau = \hat{\rho}\vec{C} = \hat{\rho}\hat{\gamma}^{-1}\vec{E}_\tau \equiv \hat{\mu}\vec{E}_\tau$. Substituting the last equality in the left-hand part of $rot\vec{E} = -ik_o\vec{H}$, we obtain the set of equations on the upper boundary in the ionosphere

$$i\frac{dE_y}{dz} + \left(\mu_{11} - k_y\tan\theta\right)E_x + \mu_{12}E_y = 0, \quad i\frac{dE_x}{dz} - \mu_{21}E_x + \left(\mu_{22} + k_x\tan\theta\right)E_y = 0. \quad (4)$$

We suppose that the EM fields behind the lower boundary vanishes for reason of large lithospheric conductivity.

Deriving boundary conditions in the problem of reflection waves from the ionosphere, we used the following suppositions. As well as in the previous case, we placed upper boundary in the satellite altitudes and lower boundary in the surface of the Earth. Through magnetospheric plasma without great losses AW can propagate only. Therefore, we consider that this waves with amplitude equal 1 fall upon the upper boundary. The waves of AW and MS types from upper boundary into upper half-space are reflected as a result of dispersion in anisotropic plasma space. Let's find upper boundary condition as well as in the previous case we found elements of matrix $\hat{\gamma}, \hat{\rho}$ from Maxwell equation. Substituted $\vec{C} = \hat{\gamma}^{-1}\vec{E}_\tau$ into $H_\tau = \hat{\rho}\vec{C}$, we found $\vec{H}_\tau = \hat{\kappa}\vec{E}_\tau + \vec{b}$ and equate with $H_{x,y} = i\mathrm{rot}\vec{E}/k_o|_{x,y}$, obtain sought equations

$$i\frac{dE_y}{dz} + (\kappa_{11} - k_y \tan\theta)\, E_x + \kappa_{12}E_y + b_1 = 0,\; i\frac{dE_x}{dz} - \kappa_{21}E_x - (\kappa_{22} + k_x \tan\theta)\, E_y - b_2 = 0.$$

We obtain the lower boundary condition using previous procedure in which we suppose that in lithospheric half-space with finite conductivity σ_l propagate electromagnetic waves of E- and H- types.

4. The Results. We shall consider corollaries of a spatial and frequency filtration of ULF EM radiation at its penetration from the lithosphere into the magnetosphere. The purpose of this work is to find typical performances of such radiation and a key opportunity of its recording.

The model distribution of a current source we choose as $J_{x,y,z} = \cosh^{-2}[(x - l_x)/L_x] \cdot \cosh^{-2}[(y - l_y)/L_y] \cdot \cosh^{-2}[(z - l_z)/L_z]$. We take typical parameters for numerical calculation: the conductivity of lithosphere $\sigma_l = 10^4 s^{-1}$, the sizes of current source in xy plane $50 \times 50km$, the size of current source in z direction $20km$, the deep of source location $40km$ and $10km$, the value of periodic boundary conditions $L_x = L_y = 2000km$, the angle of geomagnetic field inclination $\theta = 0^o, 10^o, 20^o$, the number of mode in Fourier-transform $n_x = 50, n_y = 50$, the satellites altitude $h_z = 600km$.

The shape of spatial distribution of EM field in the satellites altitude similar to the shape of spatial distribution of current source if geomagnetic field is not oblique. The area of distribution of EM field in the satellites altitude ($\sim 100 \times 100km$) much larger the area of spatial distribution of current source. This result take place also for several spaced current sources with distance from each to other about the natural sizes of sources ($50km$).

If geomagnetic field is oblique, the center of spatial distribution of EM field shifts in the line of direction of geomagnetic field proportionally to its angle value. The shape have large size ($\sim 400 - 500km$) along to direction of geomagnetic field and little size ($\sim 100km$) perpendicular to direction of geomagnetic field. As a result of shift and change of the shape of radiation from each current source the total radiation in the ionosphere from several spaced currents looks like a spot greatly elongated along a direction of the geomagnetic field.

We are interested in the case of the lithospheric current with density in which one of component is predominates in the line of direction of z - axis $J_z \gg J_\tau$, where J_τ is parallel to Earth surface component of current. In this case, the EM radiation are generated most effectively by segments of the current source with derivation $\partial J_z/\partial z$ maximum. In a case with a dominant current $J_\tau \gg J_z$ the derivation $\partial J_z/\partial z$ does not give a essential contribution of EM radiation in the ionosphere. The spatial sizes of distribution of EM radiation in the ionosphere for $J_z \gg J_\tau$ is larger than spatial sizes of EM radiation in the ionosphere for a case $J_\tau \gg J_z$. However, the value of amplitude in the case $J_z \gg J_\tau$ is bigger than in an inverse case.

The frequency filtration property of LIM system is determine with properties of the lithosphere and ionosphere. In the lithosphere due to skin-effect the amplitude-frequency characteristics (AFC) looks like $\sim A/\sqrt{\omega}$, where $A(\sigma)$ – the coefficient. In the ionosphere the AFC have maximum of penetration in the frequency range $1 - 10s^{-1}$. The precise frequency of the penetration of EM radiation through ionosphere depend on the ionospheric conditions. The main factor, which determine a value of EM field, penetrating in the magnetosphere, is electron concentration profile. If the electron concentration profile is sharp then main part of EM radiation to be reflected from it. In the magnetosphere, a main part of EM energy is propagated by waves of AW type. The harmonicses, having a AW wave number, are maximum amplitude.

As the amplitude value of a current in a lithosphere is unknown, we shall study the relation of maximum value of EM field disturbances in the ionosphere to the value of current in the lithosphere and shall mark through transmission coefficient K_i. The summery day-time ionosphere and our typical parameters of the lithosphere at the frequency $1s^{-1}$ is $K_i \sim 10^{-6}$, summery night-time ionosphere is $K_i \sim 10^{-4}$, wintry night-time ionosphere is $K_i \sim 10^{-3}$. This value have obtain for deep of lithospheric source $10km$. The relation of tangential magnetic value at ground level to the tangential magnetic value at the satellite altitudes ($600km$) frequencies $0.1s^{-1}$ about $\sim 10^2 - 10^3$, $1s^{-1}$ about $\sim 10 - 10^2$, for frequencies $\geq 10s^{-1}$ about $\sim 10^4 - 10^6$. It is necessary to mark that value of K_i strongly depend from σ_l, deep of source and density of sources to $z-$ direction. Therefore, for current source from near-surface region only with high density on the altitude and with value of current $\sim 0.1 - 1A/m^2$ the value of EM radiation $0.1 - 1nT$ at the satellite altitude $600km$ is possible.

In the magnetosphere with concentration of captured protons $0.1cm^{-1}$ with resonant energy for AW in the frequency range $1 - 10s^{-1}$, the amplification coefficient for AW equal to 1.25. The reflection coefficient faintly enough depended from the frequency in considering range $0.1 - 100s^{-1}$ and change in the range $0.8 - 0.92$. Taking into account the reflection losses and amplification due to cyclotron instability is possible to conclude: if the lithospheric origin ULF EM radiation penetrated in the magnetosphere that the amplitude of it will vary slowly.

Many obtained numerical results are close to satellite observation, see for example [**?**]. If in the lithosphere the effective mechanisms of transformation of elastic energy to EM energy take place and the current with amplitudes $0.1 - 1A/m^2$ is appear that into the magnetosphere will penetrate the EM radiation in the form of AW with amplitudes $0.1 - 1nT$. On a location of perturbed magnetic field it is easy enough to identify centre of current location and its sizes. We consider that recording and identification of lithospheric origin EM radiation is possible.

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