Specific features of the propagation of frequency modulated radio signals in the ionospheric plasma in the presence of local inhomogeneities

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Abstract. The features of the propagation of frequency-modulated radio signals reflected from the anisotropic ionosphere containing local inhomogeneities of the electron concentration are investigated. On the basis of the Hamilton-Lukin bi-characteristic method, mathematical modeling of vertical sounding ionograms was carried out both in the case of propagation of an ordinary wave and in the case of propagation of an extraordinary wave. The results of numerical simulation are presented.

1. Introduction. Formulation of the problem
Ray modeling of the propagation of frequency-modulated (FM) radio signals in the ionosphere containing local inhomogeneities has been performed. The relevance of the work is due to both the need to solve applied problems of radar, radio communication, and radio navigation, and scientific interest in the problem of studying the upper atmosphere of the Earth [1-6]. Local inhomogeneities of both natural and artificial origin and their influence on propagation characteristics play an essential role for radio engineering measurements and in predicting short-wave radio communication lines. Therefore, the improvement of mathematical modeling methods for studying the features of radio wave propagation in such plasma media, taking into account local inhomogeneities, is an important task of radio-physics [7-10].

In this work, based on the application of the Hamilton-Lukin bi-characteristic method [11-13], the problem of localization of local irregularities is studied according to the data of vertical FM sounding of the ionosphere in the decameter range. It is assumed that during the operation of a linear FM ionosonde, a radio signal delay $t_0$ recorded depends on the radiation frequency $f$ [4].

2. Electron concentration models
Figure 1 shows two models of the electron concentration of the ionosphere, considered in the work: a model with a local inhomogeneity with a lowered electron density (figure 1a) and a model with a local inhomogeneity with an increased electron density (figure 1b). The dependence of the electron concentration on the height is shown in the figures twice: as a bold line and as a gray background. A higher density of electron concentration corresponds to darker areas. The maximum of the $F$ layer is located at an altitude of $\sim 260$ km, and the maximum of the $E$ layer is at an altitude of $\sim 110$ km. Local inhomogeneities in both cases are located at an altitude of $\sim 200$ km.
3. Ray trajectories

Let us consider the features of vertical wave propagation in the anisotropic ionosphere [4, 5, 14]. The expression for the effective permittivity is determined by the Appleton–Hartree formula [15-18]. Wave vectors and ray paths are determined using the system of bi-characteristics [12, 13, 19, 20], which in this case is divided into three groups of equations, the solutions of which are found sequentially.

In figure 2a for an ordinary wave ray trajectories are plotted in the plane (x, z), in which the vector of the strength of the Earth's magnetic field also lies. It is seen that the rays deviate from the vertical, and after reflection, they return to the radiation source along the same trajectories [15, 21]. In figure 2b, the ray trajectories are plotted in coordinates (t, z) in the presence of an inhomogeneity with an increased electron concentration. Each color corresponds to a specific emission frequency from 1.6 MHz (violet) to 6.99 MHz for an ordinary wave or up to 7.65 MHz for an extraordinary wave (red).

For comparison, in figure 3a and figure 3b ray trajectories are plotted in the same coordinates for the case of an extraordinary wave and a local inhomogeneity with a lowered electron concentration.
4. Modeling of vertical sounding ionograms

The dependences of the signal reflection height on frequency for a local inhomogeneity with a low (figure 4a) and increased (figure 4b) electron concentration are shown in figures 4a and 4b. The graphs corresponding to the ordinary wave are marked in red, and the graphs corresponding to the extraordinary wave are in blue. With increasing frequency, the height of the reflection of the ray increases. With vertical incidence, the wave is reflected from the ionospheric layer when $k_z = 0$, that is, at the height $z_m$, for which $\varepsilon(z_m, 0, \omega) = 0$. Therefore, in the case of an ordinary wave, the reflection condition is the equality of the operating frequency $\omega$ to the plasma frequency $\omega_p$, which in turn is a function of $z$, since its square is proportional to the electron concentration. For an extraordinary wave, another condition takes place [15, 22]:

$$\omega_p^2 = \omega^2 - \omega_0 \omega_H,$$

where $\omega_H$ is the circular gyrofrequency. Thus, at the same frequencies, the extraordinary wave is reflected from the lower region of the ionosphere, which is illustrated in Figure 4.

Figure 3a. Ray paths of $x$-waves in the plane $(x, z)$.

Figure 3b. Ray paths of $x$-waves in the plane $(t, z)$.

Figure 4a. The dependence of the height of the signal reflection on the frequency (local inhomogeneity with reduced electron density).

Figure 4b. The dependence of the height of the signal reflection on the frequency (local inhomogeneity with increased electron density).
Figure 4a and figure 4b show two areas of graph breaks. The lower left jump at heights from ~ 100 km to ~ 150 km is formed due to the E layer and the interlayer valley between the E and F layers (see figure 1) [22]. The upper right jump, which is smaller in size, is due to local inhomogeneity. In figure 4a and figure 4b, local inhomogeneities with low and high electron concentrations are distinguished by the fact that for a low electron concentration the jump is located at a lower frequency (figure 4a), and for an increased electron concentration at a higher frequency (figure 4b).

Plots shown in figures 4 allow one to estimate the size of the valleys and, therefore, indirectly, the size of inhomogeneities by the magnitude of the jumps. Unfortunately, in the experiment, a dependence of $t_0 = 2 t_m(f)$ is observed, that is, the dependence of the time of arrival of the ray at the point of reflection on the frequency, but not a function $z_m(f)$.

The frequency dependences of the arrival time of the ray $t_m$ at the reflection point for a local inhomogeneity with a reduced electron concentration (figure 5a) and for a local inhomogeneity with an increased electron concentration (figure 5b) are shown in figure 5a and figure 5b. The graphs correspond to vertical sounding ionograms. The peaks indicate the positions of the inhomogeneities: on the left is the E layer, on the right – the local inhomogeneity.

By knowing the dependencies $t_m(f)$ and $z_m(f)$ it is not difficult to construct the dependence $z_m(t_m)$ excluding the frequency $f$. These dependences are shown in figure 6a and figure 6b. As in the previous figures, the graphs corresponding to the ordinary wave are in red, and the graphs corresponding to the extraordinary wave are in blue.
It should be noted that the relationship is discontinuous (each graph has two oblique straight lines that connect the break points) and ambiguous. The ambiguity in smooth sections is due to the fact that, on the one hand, due to an increase in the reflection height, the delay time increases, and on the other hand, the group velocity increases with increasing frequency. Therefore, it is difficult to evaluate the height of the signal reflection from the delay.

5. Conclusion
Thus, we have studied the characteristics of the particular reflected from the ionosphere-frequency modulated signals. Two-layer models of the Earth’s ionosphere containing local inhomogeneities with increased and decreased electron density are considered. Based on the numerical solution of the Hamilton-Lukin bi-characteristic system, mathematical modeling of vertical sounding ionograms was carried out both in the case of an extraordinary wave and in the case of an ordinary wave.

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