ON A NONLINEAR EFFECT IN THE PROPAGATION OF RADIO WAVES IN THE IONOSPHERE

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Abstract

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ON A NONLINEAR EFFECT IN THE PROPAGATION OF RADIO WAVES IN THE IONOSPHERE

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In the present paper we discuss, as far as we know, a nonlinear effect in the ionosphere that has not previously been considered—the occurrence of artificial gradients of the refractive index under the action of powerful radio waves propagating in it. The appearance of such gradients may exert a noticeable influence on the scattering (reflection) of radio waves that disturb the ionosphere or pass through the disturbed region.

The simplest mechanism of the phenomenon under consideration is as follows: under the action of a powerful wave there occurs a noticeable change in the electron temperature and, as a consequence, a change in the effective number of collisions of electrons with the heavy particles of the ionosphere (molecules, ions). This causes corresponding changes in the refractive index (the discussion concerns the lower part of the ionosphere and low frequencies of the propagating radio waves, when the condition $\omega \approx \nu_{\text{eff}}$ is satisfied; ω is the frequency of the propagating waves, ν_{eff} is the effective number of collisions).

Since the changes in temperature under consideration occur in a relatively thin layer of the lower ionosphere, the gradients of the refractive index formed in this region may be quite appreciable. We note that the possibility of nonlinear phenomena influencing the interpretation of data on partial reflections was pointed out in (^{1}).

To estimate the coefficient of reflection from ionospheric inhomogeneities arising in this way, one may use the Fresnel formulas. Then, in the simplest case of quasi-longitudinal propagation, we shall have (see, for example, (^{2})):

$$R_{o,x} \cong -\frac{\omega_0^2}{4\omega(\omega \pm \omega_L - i\nu_{\text{eff}})} \left\{ \frac{\delta N}{N} + i \frac{\delta \nu_{\text{eff}}}{\omega \pm \omega_L - i\nu_{\text{eff}}} \right\}. \tag{1}$$

Here $R_{o,x}$ is the reflection coefficient of the ordinary (o) or extraordinary (x) components of the radio wave; $\omega_0 = (4\pi e^2 N/m)^{1/2}$ is the plasma frequency in the reflection region (N is the electron concentration in this region); $\omega_L = \omega_H \cos\alpha$; ω_H is the gyrofrequency; α is the angle between the Earth' s magnetic field and the direction of wave propagation (the case of vertical propagation is considered); δN, $\delta\nu_{\text{eff}}$ are changes of the corresponding quantities (N, ν_{eff}) over a wavelength.

In writing formula (1), for simplicity we have neglected absorption of the wave on the path to the reflection (scattering) region and back, and, in addition, have not taken into account possible local gradients of the gyrofrequency. These omissions do not affect the estimates that follow.

To take into account the degree of influence of the propagating powerful wave, we shall use the data of experiment (^{3}), when, upon a twofold change in the power of a transmitter operating at wavelength $\lambda \approx 1300$ m, the effective number of collisions changed by the same factor. Calculations show that the change in ν_{eff} occurs mainly in an ionospheric layer several kilometers thick. Let us adopt for the estimate an overestimated val—

of this thickness $L = 10$ km. Then we have

$$\delta\nu_\phi \approx \frac{\Delta\nu_{\text{eff}}}{L}\lambda \approx \frac{\nu_{\text{eff}}}{L}\lambda,$$

and for $\nu_{\text{eff}} \approx 3 \cdot 10^6$ (this corresponds to an altitude of ~ 70 km) we obtain $\delta\nu_{\text{eff}} \approx 3.9 \cdot 10^5$. For $\omega_L \sim 8 \cdot 10^6$ we obtain $|\delta\nu_{\text{eff}}/\omega_L| \approx 0.05$. At the same time, the term $\delta N/N$, apparently, does not exceed fractions of a percent or several percent. Therefore one may assume that, in such an experiment, the contribution of artificially produced inhomogeneities to the reflection coefficient will be at least no smaller than the contribution of natural inhomogeneities of the electron concentration.

Calculations show that in a number of cases powerful waves can produce in the ionosphere still sharper gradients of the refractive index, which will influence the reflection of radio waves even more substantially. Thus, for example, at a pulse-transmitter power $P \approx 10^6$ kW, operating at a frequency of 1.7 MHz, the calculation gives a change in ν_{eff} from an altitude of ~ 70 km to an altitude of ~ 80 km by approximately a factor of 10 (the computations were carried out for a night model of the ionosphere). Under such conditions the reflection coefficient from inhomogeneities caused by heating of the ionosphere will increase by another order of magnitude in comparison with the example considered above.

At the same time it is necessary to note that at substantially lower powers of medium-wave transmitters [$P \lesssim 100 \div 500$ kW], reflections from artificially produced inhomogeneities will not play a substantial role, since the gradients of ν_{eff} arising in this case are smaller than those gradients which are always present because of the regular variation of ν_{eff} with altitude.

An interesting phenomenon may be observed in the propagation of the extraordinary component of a wave whose frequency is close to the local gyrofrequency.

As is known, such a wave will be very strongly absorbed in the very lowest part of the ionosphere and, generally speaking, the reflected wave should practically be absent (in the reflection region the field amplitude of such a wave is negligibly small). However, if the transmitter power is sufficiently large, then sharper artificial gradients of the refractive index will arise in the lower part of the ionosphere than occurs for $\omega \neq \omega_H$, and the propagating waves will be noticeably reflected from them. Thus, in the case under consideration, practically all reflection of the wave will occur not from the region $n \approx 0$, but from a lower region with an artificially produced gradient of the refractive index.*

It is of interest to consider one more phenomenon associated with the appearance of artificial inhomogeneities in the ionosphere under the action of powerful radio waves.

As is known, below the region of reflection of radio waves in the ionosphere, standing electromagnetic waves are produced. If the power of these waves is sufficiently large, then "nodes" and "antinodes" of electron temperature will be formed in the ionosphere and, consequently, "nodes" and "antinodes" of the refractive index. Such a system will constitute a kind of diffraction grating, diffraction from which can be observed both in the reception of the "disturbing" waves and in the reception of other radio waves propagating in the "disturbed" region of the ionosphere. Of course, the grating will not be strictly periodic because of the dependence of the refractive index on altitude. In addition, the diffraction pattern will be distorted by radio waves scattered from small-scale inhomogeneities. Nevertheless, it seems to us that observation of the indicated diffraction is possible and, undoubtedly, interesting.

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* As S. S. Shlyuger informed us, the reflection coefficient of the extraordinary component of sufficiently powerful radio waves, whose frequency is close to the local gyrofrequency, in experiment did in fact turn out to be substantially different from zero.

In conclusion, we note that the reflection coefficient will, generally speaking, also be affected by changes in the electron concentration in the ionosphere during the propagation of radio waves in it (^{4,5}).

A more detailed quantitative analysis of the questions touched upon here is currently being carried out.

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