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A METHOD FOR DERIVATION OF ELECTRIC FIELDS IN THE LOWER IONOSPHERE FROM MEASUREMENTS WITH A PARTIAL REFLECTION FACILITY

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Abstract

The distribution of variations in the effective electron collision frequency was obtained at the 60 – 66 km altitude range in the lower ionosphere (experimental errors within this altitude range were less than 50%). A technique for estimating the variations in atmospheric electric fields at the lower boundary of the ionosphere was developed using the experimental values of the effective electron collision frequency. From our measurements follows that the electric field $E > 0.25V \cdot m^{-1}$ in approximately 70% cases under quiet ionospheric and atmospheric conditions. These facts must be taken into account in the investigations of ionospheric processes, meteorological and propagation effects.

It is well known that electric fields can produce large disturbances in ionospheric parameters of the lower ionosphere. Our experimental results indicate that a possible cause of the appearance of big enough variations in the electron collision frequency is the effect of external electric fields of atmospheric origin. This provides an opportunity to measure electric fields in the lower ionosphere using remote sensing instruments employing radio-wave techniques.

The measurements were made with the Kharkiv State University partial reflection facility during 1978 through 1997 at frequencies of $f = 1.8 - 3.0$ MHz using a 25-micros pulse length.

The data on the effective electron collision frequency, ν, are collected at altitudes of 60, 63, and 66 km. The transcendental equation in ν

$$\frac{\overline{A_-^2}}{\overline{A_+^2}} = \frac{[(\omega+\omega_L)^2+\nu^2]^2}{[(\omega-\omega_L)^2+\nu^2]^2} \cdot \frac{(\omega-\omega_L)^2 K_\varepsilon^2\left(\frac{\omega-\omega_L}{\nu}\right) + \nu^2 K_\sigma^2\left(\frac{\omega-\omega_L}{\nu}\right)}{(\omega+\omega_L)^2 K_\varepsilon^2\left(\frac{\omega+\omega_L}{\nu}\right) + \nu^2 K_\sigma^2\left(\frac{\omega+\omega_L}{\nu}\right)} \qquad (1)$$

is being solved where $\overline{A_-^2}$ is the intensity of the extraordinary mode of partially reflected signals averaged over an 8 to 10 min interval, and $\overline{A_+^2}$ is the intensity of the ordinary mode of partially reflected signals averaged over the same interval, $\omega_L = 2\pi f_L$, f_L is the component of the electron gyrofrequency along the ambient magnetic field direction; in middle latitude experiments, the value of f_L is assumed to be equal 1.35 MHz, K_ε and K_σ are the kinetic coefficients which describe the kinetic effects in the permittivity ε and conductivity σ of the lower ionosphere. The dependences $K_\varepsilon(x)$ and $K_\sigma(x)$ can be approximated with an error of an order of a few per cent by the relations

$$K_\varepsilon(x) = 1 + \frac{a_1}{b_1 + x^2}; \quad a_1 = 0.155, \quad b_1 = 0.075, \quad 0.05 \le x < \infty;$$

$$K_\sigma(x) = 0.89 + \frac{a_2}{b_2 + x^2}; \quad a_2 = 0.027, \quad b_2 = 0.052, \quad 0 \le x \le 3.5;$$

$$K_\sigma(x) = 1; \quad 3.5 \le x < \infty.$$

where $x = (\omega - \omega_L)/\nu$ for the extraordinary mode, and $x = (\omega + \omega_L)/\nu$ for the ordinary mode. Partial reflection random measurement errors in $\nu(z)$ do not exceed the magnitude of the order of $30 - 50\%$ in the altitude range indicated above.

The processing of partial reflection signals have allowed us to establish a database that presently contains data on the electron collision frequency at 60, 63 and 66 km over more than 170 events.

If we take into account the fact that fluctuations in the number density of neutral particles and in their temperature in the ionospheric D region generally are not more than $10 - 20\%$ (in reality their most probable magnitudes are significantly smaller), then the sharp maximum in the ν/ν_m distribution should be expected within a $(1 \pm 0.2)\nu/\nu_m$ value interval (here ν_m is the model value of nue at the same altitude from which partial reflection signals are received; $\nu_m(60km) = 3.75 \cdot 10^7 sec^{-1}$, $\nu_m(63km) = 2.55 \cdot 10^7 sec^{-1}$, and $\nu_m(66km) = 1.68 \cdot 10^7 sec^{-1}$). However, taking into account random measurement errors of 70%, the values of ν/ν_m exceed the above-mentioned threshold for the conditions of our experiment. From our standpoint, a single reasonable explanation of this fact could be the hypothesis that $T_e > T_n$ (where T_e is the electron temperature, and T_n is the temperature of neutral particles) in 70% of cases in the lower part of the D region.

The most probable cause of existence of increased values of T_e can be strong atmospheric electric fields. Supposing this is true, electric field values could be estimated from ν/ν_m measurements. It is natural to suppose that the cases of $\nu = \nu_m$ correspond to the absence of electric fields.

In order to obtain the dependence of E upon ν, let us use the well-known set of balance equations in the electron number density N, the electron temperature T_e, and the number density of positive ions N^+ in a plane D-region weakly ionized plasma, and take into account the condition of quasi-neutrality

$$\frac{\partial N}{\partial t} = q_i + \nu_d \lambda N - \nu_a N - \alpha_r N^2(1+\lambda) + \frac{\partial}{\partial z}\left\{(D_t + D_a)\frac{\partial N}{\partial z}\right\}, \qquad (2)$$

$$\frac{\partial N^+}{\partial t} = q_i - \alpha_r N^2(1+\lambda) - \alpha_i N^2 \lambda (1+\lambda) + \frac{\partial}{\partial z}\left\{(D_t + D_a)\frac{\partial N^+}{\partial z}\right\}, \qquad (3)$$

$$\frac{\partial T_e}{\partial t} = \frac{2Q_e}{3kN} - \delta\nu(T_e - T_n), \qquad (4)$$

$$N^+ = N + N^-, \qquad (5)$$

where t is time, q_i is the total production rate per unit volume of positive ions resulting from the ionization of neutral atmospheric constituents, ν_d is the effective rate at which the negative ions are destroyed by electron detachment, $\lambda = N^-/N$ is the negative ion to electron number density ratio, N^- is the negative ion density, ν_a is the effective rate at which the negative ions are formed by the attachment of electrons to neutral constituents, α_r is the effective ion-electron recombination coefficient for positive ions, D_t is the coefficient of eddy diffusion, D_a is the coefficient of ambipolar diffusion, z is the altitude, α_i is the effective ion-ion recombination coefficient, k is Boltzmann's constant, Q_e/N is the average energy acquired by the electron from an external source of heating (for example, from external electric field), δ is the fractional loss of energy per electron collision, T_n is the neutral constituency temperature. In the ionospheric D region, the disturbances in the ion temperature are neglected because they are M/m times less than the disturbances in T_e (M is the average ion mass, m is the electron rest mass). For a low-frequency disturbing electric field E (that is when the inequalities $\omega_1^2 \ll \omega_L^2 \ll \nu^2$ hold, where ω_1 is the frequency of the disturbing field), the kinetic coefficient $K_\sigma(|\omega_1 \pm \omega_L|/\nu) \simeq K_\sigma(0) \simeq 1.4$, and $\sigma \simeq 1.4e^2N/m\nu$ where e is the electron charge. The multiple time-scaling analysis helps considerably simplify the initial set of equations (2)-(5) by introducing the following time scales:

$$t_1 = t_{T_e} = (\delta\nu)^{-1}, \quad t_2 = t'_N = (\nu_d + \nu_a)^{-1}, \quad t_3 = t_N = \{4q_i(\alpha_r + \lambda\alpha_i)/(1+\lambda)\}^{-1/2},$$

where t_{T_e} is an electron temperature relaxation time, t'_N is the evolution time of the disturbances in N caused by activating attachment processes, t_N is the evolution time of disturbances in N due to changes in the ionization-recombination balance. Note that in the lower ionosphere $t_{T_e} \ll t'_N \ll t_N$.

For $0 < t \leq t_{T_e}$, one can easily derive the following simplified energy balance equation:

$$\frac{d\theta}{dt} = \frac{0.97e^2E^2}{km\nu_o\theta^{5/6}} - \delta(\theta)\nu_o\theta^{5/6}(\theta - 1)T_{eo},$$

where: $\theta = T_e/T_{eo}$, $\nu = \nu_o\theta^{5/6}$, $\theta(0) = 1$, $E(t < 0) = 0$. This equation is no longer dependent on N and N^+. As a result, in a quasi-steady case, we readily obtain the following relation between E and ν:

$$E^2 = 1.67 \cdot 10^{-18}T_{eo}\nu^2\left[1 - \left(\frac{\nu_o}{\nu}\right)^{6/5}\right], \tag{6}$$

were E is measured in $V \cdot m^{-1}$, T_e in K, and ν in sec^{-1}. The subscript "o" stands for parameters of the ionosphere at $E = 0$. When deducing (6), transport processes were neglected for $L \gg 10$ m (L is a characteristic size of the disturbed region) at the heights $z \sim 60 - 70$ km. Using (6), one may determine the atmospheric electric field on the lower ionospheric boundary from the experimental values of ν. If we set $T_n = T_{eo}$, then the well known relation

$$\nu_o = 5.8 \cdot 10^{-11}N_nT_{eo}^{5/6}, \tag{7}$$

were N_n is the neutral particle number density at a particular altitude (in cm^{-3}) allows to determine the undisturbed values of ν. Usually, we assume $\nu_o = \nu_m$, although it is possible to determine ν_o from partial reflection data. The results obtained with relations (1), (6), (7) and our partial reflection data show that on the ionospheric boundary there are electric fields of $E > 0.25V \cdot m^{-1}$ in about 70% of cases. The analysis of relations (6) and (7) shows that relative random measurement errors in electric field intensity E are due to relative random measurement errors in ν, and in our experiments do not exceed 30-50 %.

The results obtained significantly improve understanding of complicated physics of the disturbed ionospheric D region. The presence of significant electric fields at the lower edge of the ionosphere (when partially reflected signals occur) indicate that an additional source of electron heating should be taken into account while investigating a disturbed ionosphere and radio wave propagation conditions. The technique described here permits the real-time derivation of changes in the electric field intensity at the lower edge of the ionosphere from partial reflection measurements.

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