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Electron collision frequency and HF waves attenuation in the ionosphere

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[1] The results of the studies of the effective electron collision frequency and HF wave attenuation in the midlatitude ionosphere carried out in the Rostov-on-Don University during the past 35 years are presented. It is found that (besides the collision absorption) the attenuation is determined also by additional dissipative and nondissipative mechanisms. The absorption is reliably determined using the gas-kinetic model of the effective electron collision frequency. The additional dissipation mechanism (anomalous absorption of ordinary waves) may occur because of their statistical transformation into slow extraordinary waves at the scattering at small-scale fluctuations of the electron concentration. The only cause of the nondissipative attenuation is the small-angle multiple forward scattering at large-scale irregularities of the ionospheric plasma. At signal propagation in the vicinity of the maximum usable frequency (MUF) the scattering provides an input into the attenuation comparable to the collision absorption. At the illumination of the ionosphere by a point source from the Earth surface, the multiple scattering leads to such distribution of the field at which the emission reflected under small angles to the vertical has an energy deficit. Presence of addition (to the collision) absorption mechanisms of HF waves attenuation leads to overestimated (as compared to the gas-kinetic ones) estimates of the electron collision frequency. The determination of the physical nature of the attenuation made it possible to develop correct methods of modeling of HF radio waves propagation in the three-dimensional inhomogeneous magnetically active ionospheric plasma and test these methods in a vast series of experiments. *INDEX TERMS:* 2487 Ionosphere: Wave propagation; 2494 Ionosphere: Instruments and techniques; 2439 Ionosphere: Ionospheric irregularities; *KEYWORDS:* Electron collision frequency; Attenuation of HF radiowaves; Physics of the lower ionosphere.

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1. Introduction

[2] The electron collision frequency with heavy particles of the ionospheric plasma is one of the most important parameters of the upper atmosphere physics. The frequency determines various kinetic effects [*Aggarwal et al.*, 1979; *Itikawa*, 1971] and the absorption of radio waves of different ranges depends on this frequency. There are two possibility of its determination: gas-kinetic modeling and empirical estimation. In both cases as a basis is taken the value called the electron effective collision frequency

$$\nu_{\text{eff}} = \frac{8}{3\sqrt{\pi}} \left(\frac{m}{2kT_e}\right)^{5/2} \int\limits_0^\infty \nu(u) u^4 \exp\left(-\frac{mu^2}{2kT_e}\right) du \qquad (1)$$

where k is the Boltzman constant; m, T_e, and u are the mass, temperature, and velocity, respectively, of the electrons having the Maxwell distribution. The collision frequency depends on the velocity:

$$\nu(u) = nq(u)u \qquad (2)$$

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where n is the number of the colliding partners and q is the effective scattering cross section depending on the velocity. Taking (2) into account, equation (1) may be presented in the form

$$\nu_{\text{eff}} = \frac{4}{3} n Q(T_e) \langle u \rangle \tag{3}$$

where

$$Q(T_e) = \left(\frac{m}{2kT_e}\right)^3 \int\limits_0^\infty q(u) u^5 \exp\left(-\frac{mu^2}{2kT_e}\right) du \tag{4}$$

is the effective scattering cross section and

$$\langle u \rangle = \sqrt{8kT_e/\pi m}$$

is the mean velocity.

[3] Below we will use the denotation $\nu_{\text{eff}} = \nu_e$. The total effective collision frequency is the sum of partial values

$$\nu_e = \sum_X \nu_{eX}$$

the summation being performed over all heavy components X of the plasma. For the D region where the electron temperature is low enough, the dependence of the collision frequency with molecules N_2 and O_2 on the velocity is well approximated by [*Budden*, 1965]

$$\nu(u) = \nu_M \frac{mu^2}{2kT_e}$$

which according to (1) gives $\nu_e = (5/2)\nu_M$. The ν_M parameter is called a frequency of collisions of monoenergetic electrons.

[4] At the gas-kinetic modeling of the effective electron collision frequency, to calculate values ν_e, one needs to know the cross sections of the electron scattering at heavy particles of the plasma, their concentration, and electron temperature [*Aggarwal et al.*, 1979; *Banks,* 1966; *Gurevich and Shvartsburg*, 1973; *Itikawa*, 1971; *Mantas*, 1974]. It is assumed at an experimental determination that the radio wave attenuation in the ionosphere is caused exceptionally by the absorption of their energy due to the electron collisions to ions and neutral particles of the upper atmosphere. Therefore it is accepted that using the data on absorption, one can obtain empirical estimates of ν_e. The radio wave absorption is measured by different ways: by the A1 method (ground-based vertical pulse sounding), A2 method (registration of the intensity of space radio noises), at the oblique sounding and at the propagation of waves between a rocket and Earth surface, and in the cross-modulation experiments.

[5] The first most complete comparison of the empirical and gas-kinetic results for the D and E regions showed [*Thrane and Piggott,* 1966] that the agreement between the two has place only in the D region. In the E region, beginning approximately from 100 km, the experimental values exceed the theoretical (gas-kinetic) ones. The discrepancy increases with height reaching a factor of 10 at a height of 120 km [*Thrane and Piggott*, 1966]. The empirical estimates of the collision frequency in the D region were obtained on the basis of rocket experiments and measurements by the cross-modulation method. In the E region the estimates were obtained mainly on the basis of the vertical sounding.

[6] The comparison of the theory and experiment by *Setty* [1972] and *Aggarwal et al.* [1979] confirmed the conclusions of *Thrane and Piggott* [1966] and found the presence of similar discrepancies in the F region. The majority of the experimental results for the F region were obtained by the A1 method. The evaluations of ν_e were mainly performed by the Appleton method or by its various modifications. [*Setty*, 1972; *Thrane and Piggott*, 1966]. Values of ν_e in the F region were also determined from the absorption measurements by the A2 method [*Benediktov and Tolmacheva*, 1975; *Gel'berg*, 1986; *Gel'berg et al.*, 1985; *Kumari and Mahajan,* 1971; *Saha*, 1971; *Skrebkova*, 1975; *Zhulina*, 1982]. It was found that at high [*Gel'berg*, 1986; *Gel'berg et al.*, 1985; *Zhulina*, 1982] and low [*Kumari and Mahajan*, 1971; *Saha*, 1971] latitudes the empirical estimates of ν_e also exceed the gas-kinetic ones and only at middle latitudes do they agree with each other [*Benediktov and Tolmacheva*, 1975; *Skrebkova*, 1975]. As far as the vast majority of the experimental results were obtained by the A1 method, the above indicated contradictions initiated the following questions. May the discrepancies be caused by incorrect taking into account of the methodical errors while interpreting the absorption measurements by the A1 method in the ν_e terms [*Thrane and Piggott*, 1966]? Do there exist "hidden" or incorrect parameters leading to incorrect estimates of the gas-kinetic values of the collision frequency [*Setty*, 1972; *Thrane and Piggott*, 1966]?

2. Beynon Idea

[7] The idea of exclusion of possible systematic errors is from *Beynon and Rangaswamy* [1968] as follows. To determine the collision frequency, one needs absolute measurements of the radio wave absorption L at their vertical reflection from the ionosphere (the A1 method). The absorption is related to the electron concentration N and collision frequency ν_e via the absorption coefficient by

$$L(f) = 2 \int\limits_{h_0}^{h_r} \kappa[f, N(h), \nu_e(h)] dh \tag{5}$$

where f is the wave frequency, h_0 is the height if the ionosphere bottom, and hr is the height of the signal reflection. Knowing the frequency dependence of the absorption $L(f)$ and having vertical profile of the electron concentration $N(h)$, one can obtain from (5) the vertical profile of the electron collision frequency $\nu_e(h)$. In the case when the $\nu_e(h)$ is known, one can determine the $N(h)$ profile.

[8] The problem of $\nu_e(h)$ profile determination was realized in the following way [*Beynon and Rangaswamy*, 1968]. The radio wave absorption at two frequencies $f_1 < f_0E$ and $f_2 > f_0E$ was measured. The signals at the first and second

frequencies were reflected at the bottom of the E and F regions, respectively. Ionograms $h'(f)$ of the vertical sounding (VS) were registered simultaneously. It was assumed that the vertical profile of the electron collision frequency is known from the bottom of the D region up to the reflection height $h_r(f1)$ of the signal at the first frequency f_1. Therefore the absorption $L(f_1)$ together with the virtual height $h'(f_1)$ were used to find the N_0 and α parameters of the model $N(h)$ profile

$$N(h) = N_0 \exp[\alpha(h - h_0)^2] \quad (6)$$

where N_0 is the electron concentration at $h_0 = 60$ km. The values of the N_0 and α parameters were found by solving the system of equations:

$$L(f_1) = 2 \int_{h_0}^{h_r(f_1)} \kappa[f_1, N_0, \alpha, \nu_M(h)]dh \quad (7a)$$

$$h'(f_1) = \int_{h_0}^{h_r(f_1)} \mu'(f_1, N_0, \alpha)dh \quad (7b)$$

where μ' is the group refraction index and ν_{M} is the collision frequency of monoenergetic electrons [*Budden*, 1965]. The absorption was calculated using the generalized magnetoion theory [*Budden*, 1965]. The obtained model profile $N(h)$ was used for calculation of the input into the absorption at a frequency f_2 of the height interval from h_0 to $h_r(f_1)$.

[9] Then taking into account model (6), the $N(h)$ profile in the E and F regions was restored from ionograms. At the final stage, the $\nu_e(h)$ profile was fitted corresponding to the absorption $\Delta L(f_2)$ falling on the height interval from $h_r(f_1)$ to $h_r(f_2)$. The determined by this method separate $\nu_e(h)$ profiles in the height interval 100–150 km agree with the gas-kinetic estimates [*Beynon and Rangaswamy*, 1968].

3. Multifrequency Polarization Measurements of the Radio Wave Absorption by the A1 Method

[10] The Beynon idea was used in the early 1970s for systematic studies of the effective collision frequency in the ionosphere. Till then, experience had been accumulated in measurements of the absorption by the A1 method first at two and then at five frequencies simultaneously [*Svechnikov et al.*, 1972]. To study the radio wave absorption and, respectively, $\nu_e(h)$ profiles in the entire thickness of the ionosphere, measurements of the absorption at many frequencies of the F region were required. Among them, there should have been frequencies at which the group delays of signals of the ordinary and extraordinary rays were the same, that is, a polarization fading took place. For getting rid of these signals it was necessary to separate signals by the polarization. A polarization ionosonde was created which registered separately the signals of the ordinary (o) and extraordinary (x) polarizations [*Danilkin et al.*, 1974]. An example of the first publication of a polarization ionogram is shown in Figure 1.

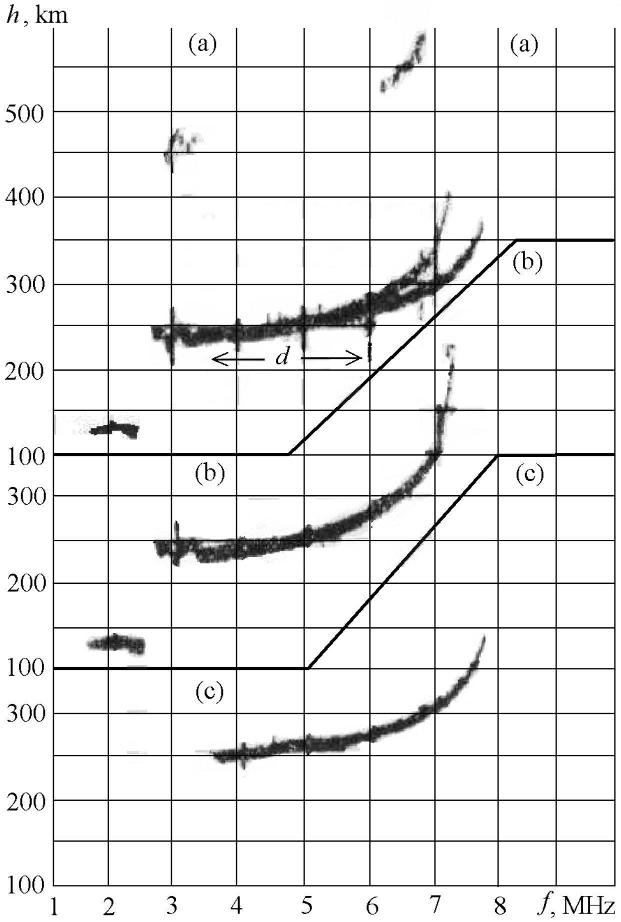

Figure 1. Example of the first published ionogram [*Danilkin et al.,* 1974] in which the ordinary and extraordinary components of the signal reflected from the ionosphere are detected separately: (a) routine ionogram, (b) only ordinary component; and (c) only extraordinary component.

[11] To determine the frequency dependencies of the radio wave absorption, the amplitudes of the reflected signals were measured simultaneously at 10 frequencies. Two regimes of operation were used. In the first regime all measurements used only "O" signals. In the second regime measurements were conducted using signals of both polarizations at five frequencies each. All frequencies for the "x" signals were chosen to be by 0.7 MHz higher than for the "O" signals. In the geographical conditions of Rostov-on-Don station this provided approximate equality of the reflection height.

[12] The calibration of the measurements, i.e., determination of the equipment constant, was conducted for all frequencies below 3 MHz using multiple reflections. For higher frequencies the calibration was performed by the polarization method [*Danilkin and Faer*, 1972]. To exclude rapid signal fading, an averaging over 15- or 30-min intervals of measurements was used. The influence of focusing or defocusing was excluded by running averaging over a 90-min pe-

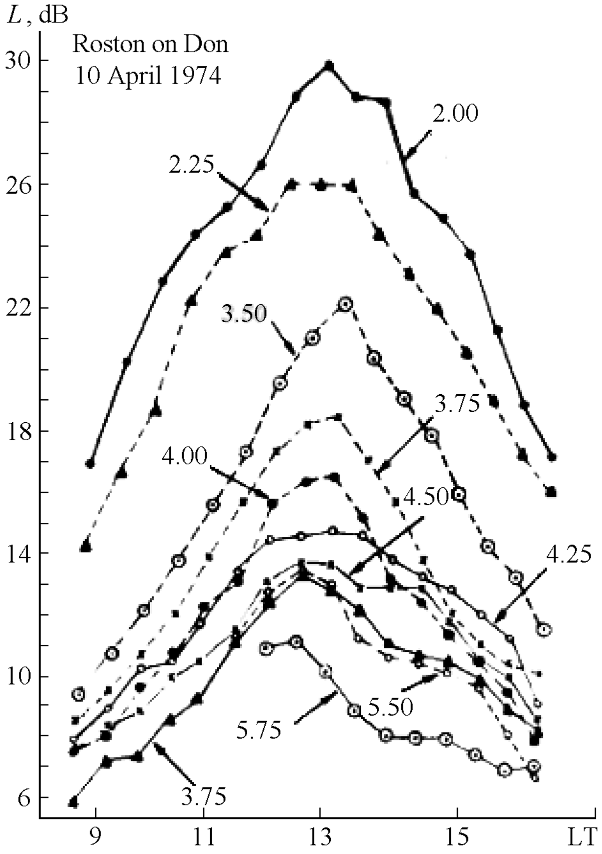

Figure 2. Diurnal variations of the radio wave absorption with ordinary polarization at 10 frequencies (in MHz).

riod of observation [*Berezin*, 1964; *Berezin and Gusev*, 1961; *Givishvili and Shaulin*, 1975]. An example of measurements of the absorption of "*o*" waves at 10 frequencies at Rostov on Don at the 30-min interval of averaging is shown in Figure 2.

4. Reconstruction of *N(h)* Profiles From the Vertical Sounding Data

[13] Determination of $\nu_e(h)$ profiles from the data on the frequency dependency of the absorption requires solution of the accompanying problem: reconstruction of $N(h)$ profiles. This problem was solved by us in the following way.

4.1. *D* Region

[14] The ionization vertical profile in the D region was found by the modified method of *Beynon and Rangaswamy* [1968]. The essence of the modification was the following [*Danilkin et al.*, 1977]. Instead of model (6) the approximation

$$N(h) = N_0 \exp \frac{h - h_0}{H} \qquad (8)$$

was used which agree well with rocket measurements. The parameter N0 was fixed and taken equal to 100 cm^{-3}. The values h_0 and H were considered as unknown. They were found from the requirement of coincidence of the left-hand and right-hand sides of (7a) at the condition of minimum of the functional

$$S(h_0, H) = \sum_{i=1}^{n} [h'(f_i) - h'_{\mathrm{theor}}(f_i, h_0, H)]^2 \qquad (9)$$

where h'_{theor} are the calculated values of the virtual heights of the "*o*" trace of the ionogram at the given h_0 and H parameters. In other words, the problem of a search for conventional minimum was solved. The working frequencies f_i were taken from the range from $f_{\min}$ to $f_1 + 0.2$ MHz with a step of about 0.1 MHz. Such procedure made it possible to reduce by several times the impact of random errors on the measurements of the virtual heights [*Danilkin et al.,* 1981].

4.2. *E* Region

[15] For the calculation of the vertical profile of the electron concentration in this layer both traces in the ionogram were used. The plasma frequency range from f_1 to f_oE was split by the net frequencies f_i to elementary intervals $\Delta f_i = f_{i+1} - f_i$ about 0.2 MHz wide. It was assumed that in all these intervals except the last one the electron concentration depends on height in a linear way. A parabolic distribution was accepted in the last interval. First, the part of the virtual heights $\Delta h'(f)$ corresponding to the E layer was found by a subtraction of the input of the ionospheric region located below the level of the reflection of the wave f_1, used for the measurement of the absorption. Then by the least squares method the true heights h_i corresponding to the net frequencies f_i were determined. To do that, the functional was minimized:

$$\Phi(\mathbf{z}) = (\hat{M}\mathbf{z} - \Delta\mathbf{h}')^T (\hat{M}\mathbf{z} - \Delta\mathbf{h}') \qquad (10)$$

where the T index means transposing and vectors $\mathbf{z}$ and $\Delta\mathbf{h}'$ are

$$\mathbf{z}^T = (h_2, h_3, \ldots, h_m E)$$

$$(\Delta\mathbf{h}')^T =$$

$$[\Delta h'_0(f_2), \ldots, \Delta h'_0(f_n), \Delta h'_x(f_1^x), \ldots, \Delta h'_x(f_n^x)]$$

The matrix $\hat{M}$ has a structure

$$\hat{M}^T = (M_0^T, M_x^T)$$

where the elements of each matrix $\hat{M}_o$ and $\hat{M}_x$ correspond to the accepted approximation of $N(h)$ in the elementary intervals. The solution has the form

$$\mathbf{z} = (\hat{M}^T \hat{M})^{-1} \Delta\mathbf{h}' \qquad (11)$$

4.3. Valley and F Region

[16] The calculation of the nonmonotonous $N(h)$ profile above the maximum of the E region was performed by the same method as for the E region. First the input of the region located below into the virtual heights of the "o" and "x" signals reflected from the F region was excluded. Then by the least squares method the $N(h)$ profile was calculated. The only difference was that the first columns of the $\hat{M}_o$ and $\hat{M}_x$ matrix depended on minimum electron concentration N_v in the valley. In other words the minimized functional has the form

$$\Phi(\mathbf{z}, N_\nu) = (\hat{M}\mathbf{z} - \Delta\mathbf{h}')^T(\hat{M}\mathbf{z} - \Delta\mathbf{h}') \tag{12}$$

For the region unseen by ionosondes the models of monotonous distribution, plateau with $N_v = N_mE$, and triangle dependencies of N on h within the valley at $N_v < N_mE$ were accepted in a sequence. For every model and each value of N_v decreasing with a small step the current solution was found using formula (11). The solution providing in (12) the minimum possible value was accepted as a final solution.

5. Reconstruction of $\nu_e(h)$ Profiles

[17] The condition $\nu_e/(2\pi f) \ll 1$ is fulfilled for the sounding signals in the E and F ionospheric regions It makes it possible to simplify considerably calculations of radio wave propagation. It was shown first numerously [*Beynon and Jones*, 1965; *Titheridge*, 1967] and later analytically [*Vodolazkin et al.*, 1989a, 1989b] that the use of the linearized in terms of ν_e absorption coefficient κ in formula (5) makes it possible to obtain values which almost do not differ from the results of the full-wave theory. Therefore for the E and F regions expression (5) may be presented in the form

$$L(f) = \int_{h_0}^{h_r} K[f, N(h)]N(h)\nu_e(h)dh \tag{13}$$

where K is the kernel which does not depend on the collision frequency.

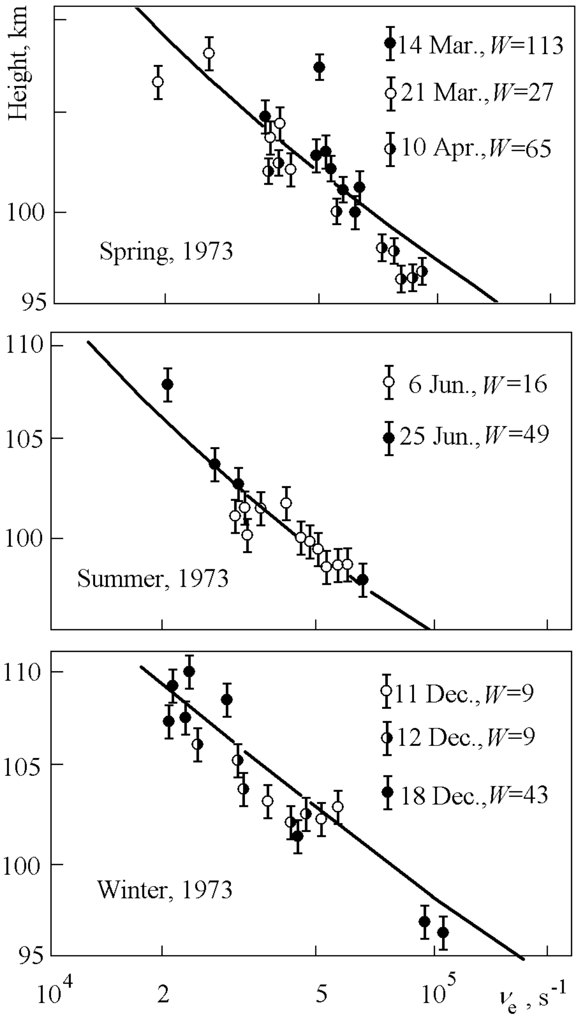

Figure 3. Vertical profiles of the effective electron collision frequency in the E layer obtained in different seasons of 1973.

5.1. E Layer

[18] The determination of the effective collision frequency in this layer was performed to check the agreement between the gas-kinetic evaluations and the "point" (that is, related to a narrow height interval) empirical estimates [*Danilkin et al.*, 1978]. To do this, the absorption measurements of "o" waves at two frequencies $f_1 = 2$ MHz and $f_2 = 2.25$ MHz were used. The absorption at the f_1 frequency and virtual heights of the "o" trace in the ionogram from the frequency interval including f_2 were the initial data for the determination of the h_0 and H parameters of the model (8). After restoration of the $N(h)$ profile which was assumed to be applicable up to the reflection level $h_r(f_2)$ of the second frequency, for this frequency the input into the absorption of the region $h \leq h_r(f_1)$ and the absorption $\Delta L(f_2)$ for the interval from $h_r(f_1)$ to $h_r(f_2)$ were calculated. Taking into account the linearized formula (13) the absorption was presented in the form [*Danilkin et al.*, 1978]

$$\Delta L(f_2) = \bar{\nu}_e \int_{h_r(f_1)}^{h_r(f_2)} K[f, N(h)]N(h)dh = \bar{\nu}_e \frac{H}{c} G(f_1, f_2)$$

where $\bar{\nu}_e$ is some mean value of the collision frequency over the height interval from $h_r(f_1)$ to $h_r(f_2)$ and G is the value depending for each observation point only on the working frequencies f_1 and f_2. The value of was easily estimated from the above formula. Because of regular diurnal variations of the electron concentration and also variations in solar activity the position of the interval $\Delta h = h_r(f_2) - h_r(f_1)$

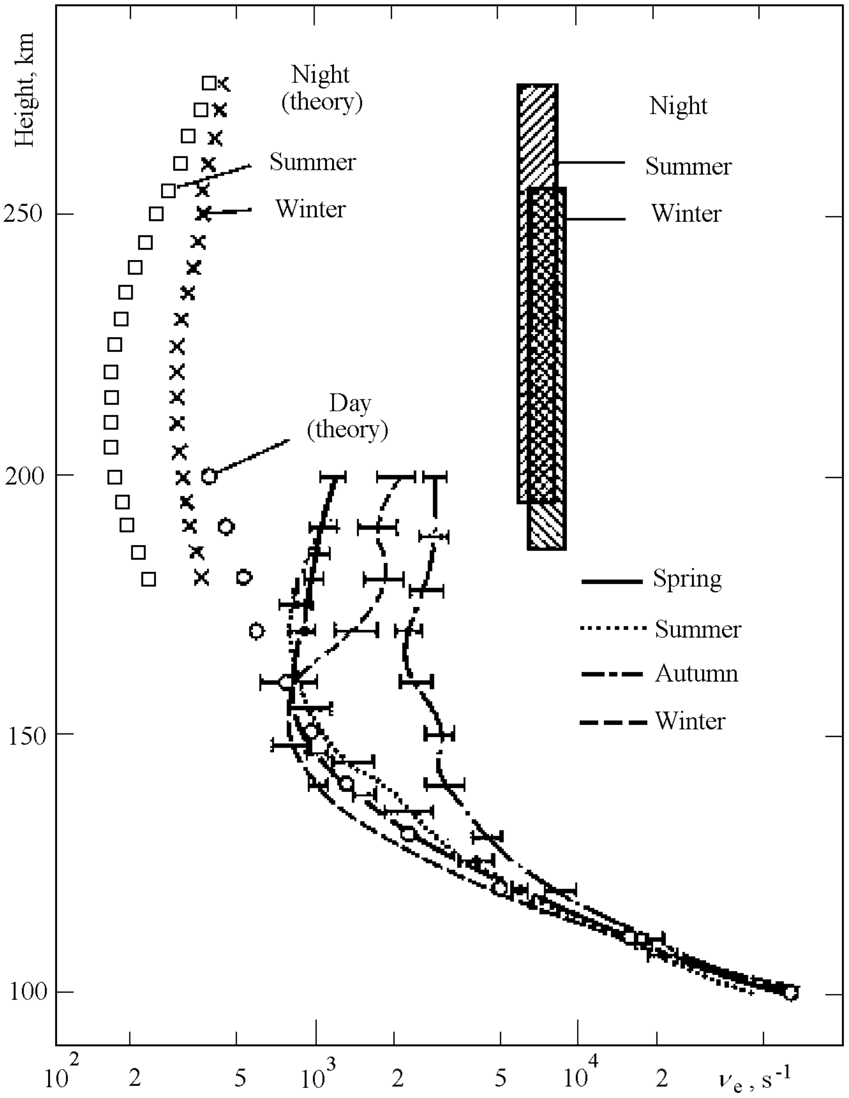

Figure 4. Experimental profiles of the effective electron collision frequency in various periods of 1979.

also varied and that made it possible to study the vertical profile of the collision frequency.

[19] The results of the determination at Rostov on Don for three seasons (spring, summer, and winter) of 1973 are presented in Figure 3. For the sake of comparison the results of the gas-kinetic calculations are also shown in Figure 4. One can see that a satisfactory agreement exists between the theory and experiment. Similar conclusions follow from the experimental estimates of ν_e by *Beynon and Jones* [1965], *Ganguly* [1974], and *Ganguly and Jain* [1975]. The analysis of the specifics of the Appleton method showed [*Vodolazkin et al.*, 1989a] that the results obtained on its basis are not reliable in the E layer. The error due to the errors in measurements of virtual heights reaches 100%. At the same time, similar estimates for the maximum of the F region should be taken into account because their errors are only a few tens of percents and do not cover the discrepancies between the theory and experiments.

5.2. Valley and F Region

[20] The experimental $\nu_e(h)$ profiles were determined in several stages. At the first stage simplified calculation schemes [*Danilkin et al.,* 1975, 1976] of radio wave absorption measurements only of the ordinary polarization and only in the daytime were used. In all intervals between the adjacent levels of radio wave absorption h_i and h_{i-1} the same approximation was accepted

$$\nu_i(h) = \nu_{i-1} \exp[a_i(h_i - h_{i-1})] \qquad (14)$$

For the height interval including the valley it gave at the bottom of the F region the collision frequencies below the gas-kinetic ones. Later on when it was found that empirical estimates of ν_e cannot be less than the gas-kinetic ones, this model for the interlayer region was substituted by

$$\nu_i(h) = \nu_{i-1} \exp[a_i(h_i - h_{i-1})^p] \qquad (15)$$

with $p > 1$ [*Vodolazkin et al.*, 1983]. Therefore at the second stage the calculation of $\nu_e(h)$ profiles was performed using the approximations (14) and (15). Using this method the [*Vodolazkin et al.*, 1983] empirical model was created. It uses the data on the absorption of "*o*" waves obtained at 10 frequencies from the 2.00–6.25 MHz range during 1973 ($F_{10.7} = 100$). It manifests only the seasonal variations of $\nu_e(h)$ below 200 km in the daytime. The model was obtained by an averaging of 51, 17, and 20, and 20 individual $\nu_e(h)$ profiles for spring, summer, fall, and winter, respectively. The results are presented in Figure 4.

[21] Restoration of individual $\nu_e(h)$ profiles and their averaging showed that the discrepancy between the experiment and theory exists only in the F region, the empirical dependencies showing smaller vertical gradient. So a special method of calculations of $\nu_e(h)$ profiles only in the F region was developed [*Vodolazkin et al.,* 1979] for the model

$$\nu_e = \text{const} \qquad (16)$$

The averaged results of the ν_e determination for winter and summer of 1979 obtained on the basis of the measurements of the "*o*" waves absorption in the after dusk period are also presented in Figure 4. One can see that in the F region the empirical estimates of ν_e exceed the gas-kinetic ones by a factor of 2–6 and more than by a factor of 10 in the daytime and at night, respectively. In the gas-kinetic calculations of $\nu_e(h)$ for the given geophysical conditions one has to use model values of T_e and concentrations of the multicomponent atmosphere. They correspond to some average situation and for each particular case may have considerable differences, the latter fact leading to a large uncertainty in $\nu_e(h)$. So rocket-ground-based experiments have been conducted. They had two goals. The main one was to obtain the data (concentration of electrons and neutral particles, and electron temperature) for the gas-kinetic calculations of the collision frequency. The second goal was to exclude the errors appearing at calculating of nonmonotonous $N(h)$ profiles from the data of the ground-based vertical sounding (VS) and to check the accuracy of their reconstruction in the entire inner ionosphere.

[22] It was shown in the rocket-ground-based experiments that the use of direct measurements of the needed parameters for gas-kinetic estimates in the F region does not eliminate the discrepancy between the theory and experiments. The discrepancy still takes place reaching an order of magnitude and more [*Danilkin et al.*, 1989]. An example of the comparison of such results for one of rocket flights is presented in Figure 5 [*Biryukov et al.*, 1980]. Thus, in the F region all experimental estimates of the collision frequency based on the VS by "*o*" waves exceed the gas-kinetic evaluations. The comparison of the rocket $N(h)$ profiles to the profiles based on the VS data showed their satisfactory agreement [*Danilkin et al.*, 1989] (see Figure 6). This means that reconstruction of $\nu_e(h)$ profiles on the basis of only VS data does not introduce rough errors.

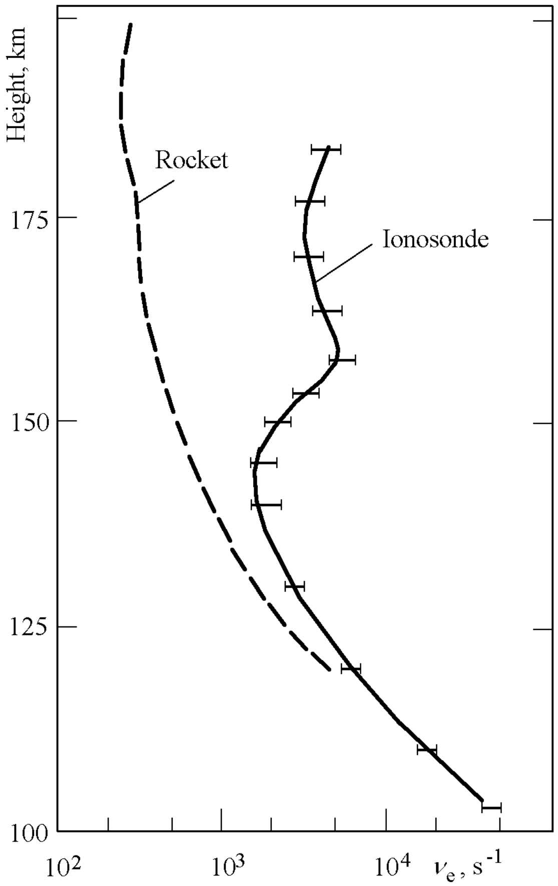

Figure 5. Vertical profile of the effective electron collision frequency in the ionosphere based on the polarization measurements of the radio wave absorption at 10 frequencies and $N(h)$ profiles measured by the dispersion interferometer method in the rocket flight.

6. Analysis of the Discrepancies Between the A1 Method Data and Theory

[23] On of the first hypotheses aimed to agree the gas-kinetic and empirical estimates of the effective electron collision frequency for the F region was suggested by *Setty* [1972]. Because of the complication and low reliability of laboratory measurements of the electron scattering cross sections at atoms of oxygen Q_{O} he have made their correction (revision) in the direction of a considerable increase relative to the known values [*Banks*, 1966]. The hypothesis was checked by *Setty* [1972] in the following way. Using the empirical estimates of ν_e for the maximum of the F region, known values of N, model values of the neutral concentration and electron temperature T_e, he reached (because of the increase of Q_{O}) a complete agreement between the theoretical and experimen-

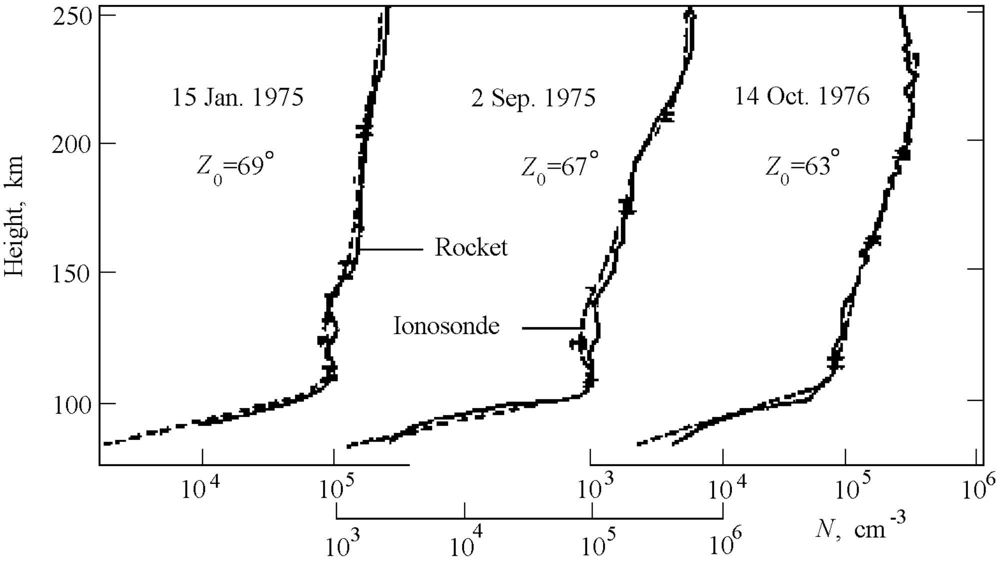

Figure 6. $N(h)$ profiles in the ionosphere obtained by the dispersion interferometer method in the rocket flights and calculated on the basis of the polarization ionograms measured by the ionosonde located in the vicinity of the rocket launching.

tal results. Since T_e was changing from one measurement to another, determination of the $Q_O(T_e)$ became possible. It was found that on the whole the cross section should be increased by more than two orders of magnitude [*Setty*, 1972].

[24] The *Setty* [1972] hypothesis was checked by *Vodolazkin et al.* [1983], who used the empirical model of $\nu_e(h)$ for four seasons. For every season a complete agreement between the theoretical and experimental results at heights of 150–200 km was obtained. Because of T_e variations with height a determination of the $Q_O(T_e)$ became possible. One could expect that (if the Setty hypothesis is correct) the $Q_O(T_e)$ functions for all seasons would be similar and agree with the *Setty* [1972] estimates. However, it appeared that first, $Q_O(T_e)$ varies from one season to another and, second, the character of the temperature dependence differs from the results of *Setty* [1972]. In the case of *Vodolazkin et al.* [1983], $Q_O(T_e)$ increases with an increase of the electron temperature, whereas *Setty* [1972] obtained a decrease of $Q_O(T_e)$ with T_e. Therefore one cannot reach a coincidence of the theory and experiment reconsidering the scattering cross sections.

[25] It was found later that the use of the absorption of waves of different polarizations obtained at the same time to reconstruct $\nu_e(h)$ profiles gives different results. The collision frequency estimated from the "o" waves absorption always is higher than analogous results obtained using "x" waves. [*Denisenko et al.*, 1987a]. This fact initiated a modernization of the *Vodolazkin et al.* [1983] empirical model. On the basis of 392 simultaneous of simultaneous measurements of the absorption of "o" and "x" waves in the daytime in 1988 ($F_{10.7} = 140$) empirical models of $\nu_e(h)$ at heights of 100–200 km were created for each month [*Vodolazkin et al.*, 1993]. In the same way as in the *Vodolazkin et al.* [1983] model the experimental estimates exceeded the gas-kinetic ones above 150 km. The mean empirical values of ν_e for the 150–200 km height interval are shown in Table 1.

[26] Table 1 shows that for the conditions of Rostov on Don the collision frequencies in the F region measured using "o" waves are by a factor of 2–2.5 higher than the estimates obtained using "x" waves [*Vodolazkin et al.*, 1993]. The latter are higher than the gas-kinetic ones by a factor of 5–6. This is confirmed by the results of independent measurements [*Setty et al.*, 1970].

[27] The dependence of the results of the ν_e diagnostics on the polarization of the sounding signals led to the conclusion on the need for a search of collisionless mechanisms of HF wave attenuation. Therefore a hypothesis was suggested that the cause of the discrepancy between the "o" and "x" estimates lies in the anomalous absorption of "o" waves caused by their transformation into slow extraordinary (z) waves due to the scattering at irregularities of the electron concentration in the vicinity of the reflection level [*Denisenko et al.*, 1987a, 1987b]. It was found that to explain the observed effects the relative fluctuations of the electron concentration should be $(2 - 4) \times 10^{-3}$ [*Vodolazkin et al.*, 1989b]. The latter value does not exceed the observed fluctuations. Indirect confirmation of the transformation effect may be found in several publications [*Denisenko et al.*, 1987b, 1993; *Korovin*, 1984]. *Korovin* [1984] found a pronounced correlation between the observations of the enhanced derivative absorption of "o" waves during VS of the ionosphere in the vicinity of the F region critical frequency (the R condition) and appearance of field-aligned irregularities with the transverse dimensions of a few meters detected by the aspect scattering method in the VHF range. *Denisenko et al.* [1987a, 1987b, 1993] explained the presence of diffusive traces in ionograms of topside sounding by the transformation effect of "o" waves into "z" waves (We discuss the frequency inter-

Table 1. Mean Empirical Values of ν_e for the 150–200 km Height Interval[†]

Signal	Months											
Polarization	I	II	III	IV	V	VI	VII	VIII	IX	X	XI	XII
Ordinary	6.8	7.1	7.1	6.1	4.6	4.2	4.2	4.6	5.8	6.8	7.1	6.3
Extraordinary	2.6	3.1	3.0	2.3	2.2	2.2	2.5	2.2	2.6	3.0	2.8	2.5

[†] In units 10^3 s^{-1} for high solar activity (1988, $F_{10.7} = 140$).

val from $f_{\max} = \max(f_{ps}, f_H)$ to f_{UHF}, where (f_{ps} and f_H) are the plasma frequency and gyrofrequency of electrons, respectively, and f_{UHF} is the upper hybrid frequency in the vicinity of the satellite.) The idea of attracting of collisionless absorption mechanisms appeared to be fruitful while interpreting the results of the HF absorption measurements by the A2 method in the high-latitude ionosphere. *Gel'berg* [1986] and *Berezhko et al.* [1987] showed that the extra attenuation is due mainly to the interaction of the waves to the plasma turbulent pulsations.

7. Oblique Sounding Experiments

[28] The explanation of the anomalous values of the "o" waves absorption measured by the A1 method was able to solve only part of the problem. It was necessary to find the cause of the discrepancy between the gas-kinetic values of the collision frequencies and the "x" evaluations and also the results of the oblique diagnostics [*Anyutin et al.*, 1985; *Baulch and Butcher*, 1988]. In this case the waves do not reach the transformation region. Special experiments were conducted on simultaneous diagnostics of ν_e by "x" waves using the methods of vertical and oblique (OS) sounding of the ionospheric F region [*Beley et al.*, 1990]. The essence of the experiments was the following.

[29] The midlatitude path Vladikavkaz–Kharkov about 940 km long was used for OS. Monochromatic waves at frequencies close to 10 and 13.5 MHz were emitted at Vladikavkaz. The signals were received near Kharkov by the decameter radiotelescope UTP-2. The interference structure of the field at the passing of the dead zone boundary over the reception point was registered. The depth of its modulation (the electron concentration vertical profile being known) was used to find the effective collision frequency in the F region. The necessary conditions were realized in the dawn and dusk hours when the D and E regions were weakly pronounced. In Rostov on Don, approximately at a distance of 130 km from the middle point, a vertical diagnostics of the collision frequency by the A1 method was conducted using waves of ordinary and extraordinary polarization. The experiments were carried out during 10 days in wintertime and gave the following results.

[30] The empirical estimates of the collision frequency according to the data of OS diagnostics did not coincide with the results of the VS diagnostics. Moreover, it was found that the OS estimates increase with an increase of the sounding frequency and that the attenuation of OS signals varies proportionally to the frequency squared and exceeds the theoretical evaluations by a factor of about 10–20. Thus the idea on the existence of "hidden" parameters not taken into account by the gas-kinetic theory was finally buried. The character of the frequency dependence of the attenuation led to the conclusion that at propagation of radio waves with frequencies close to MUF the main input into the energetic losses in the F region is provided by the multiple scattering of the waves into the topside ionosphere at irregularities of the electron concentration with the dimensions much larger than the wavelength [*Beley et al.,* 1990; *Bronin et al.*, 1991, 1993].

[31] Besides the experiments on determination of the attenuation of HF waves from relative measurements of the signal levels at vertical and oblique sounding of the ionosphere, numerous measurements of the absolute values of the field magnitude of HF transmitters were conducted in the Rostov State University. The experiment was carried out at five midlatitude paths from 15 to 500 km long. Different orientation of the paths relative the field-aligned irregularities provided different conditions for the scattering. The effect of the transformation of "o" waves into "z" waves was possible only at the shortest path. In all other cases the effect was impossible. The experiment covered periods of both low and high solar activity. The working frequencies were in the 0.5–0.95 MUF range. This provided reflection of the entire emission (including the scattered component) back to the Earth surface. The choice of such small path length and working frequencies provided signal penetration up to the heights of the F-region maximum. In this very condition the collision absorption, which depends on the profile, is manifested in the maximum degree.

[32] The experiment included measurements of the mean values of the field strength (E) with temporary separation of the rays at synchronous pulse oblique sounding in the conditions of the checking of the emitted power and state of the ionosphere. The checking of the state of the ionosphere was provided by the height-frequency characteristics of VS in the point of emission. The standard derivative of the equipment determined by the accuracy of the checking of the emitted power and measurements of the field strength did not exceed 2 dB.

[33] The experiment included 12 stages and was conducted both in the daytime and at night. The measurements at each stage were conducted every day at the same time at 8 fixed frequencies, not less than 15 min at each frequency. The duration of one stage was 10–15 days and was determined by the condition that the statistical error of the averaging of E over all days should not exceed the equipment error.

Table 2. Results of the Experiments on Measurements of the Field Strength of HF Transmitters

Exp.	Path Length, km	Magnetic Azimuth, deg	Conditions of the Experiment Conduction					
			Working Frequency Range, MHz	Year/Month	W	n	ΔL, dB	Stage
1	15	180	3.4–6.8	1987/5, 6	6	283	0.4	1
			3.4–5.3	1987/6, 7	12	285	−0.4	3
			3.4–6.8	1987/9	18	151	0.3	5
			4.1–9.2	1978/3, 4	90	145	1.3	6
			3.4–10.7	1978/12; 1979/1	133	391	−2.0	9
2	183	143	3.4–5.3	1987/6, 7	12	261	−2.8	2
			3.4–6.8	1987/9	18	129	1.2	4
3	195	17	3.4–9.2	1978/6, 7	93	161	−0.6	7
4	378	−32	3.4–10.8	1978/9, 10	121	316	−1.2	8
			3.4–12.3	1979/3, 4	124	288	−0.9	10
5	493	8	4.1–12.3	1979/10	157	88	−3.6	11
			4.1–9.2	1980/6, 7	124	102	0.3	12

On the whole, 2600 15-min series were conducted and processed. This makes it possible to consider the measurement results statistically significant. The information on the paths and stages, solar activity (W), frequency ranges, and the number of the 15-min series n is presented in Table 2. The detailed information on the experiments was published by *Barabashov et al.* [1997].

[34] The values of the field strength of discrete rays obtained in the scope of the experiment were compared with the calculated values by the method proposed by *Barabashov et al.* [1983]. The method provides determination of the loss along the ray trajectories in the magneto-active spatially irregular ionosphere. A constant profile close to the gas-kinetic one was used in the calculations. The coincidence degree of the measured and calculated values of the field strength was estimated by the value

$$\Delta L = \langle E_e - \langle E_t \rangle \rangle$$

where $\langle E_e \rangle$ and $\langle E_t \rangle$ are the averaged over the stage experimental and calculated values of the field strength in dB. Here is the field strength derived from the hourly mean data of the current VS. The results of the ΔL evaluation by this method are shown in Table 2. The values of ΔL averaged over all measurement stages for solar maximum and minimum were 1.2 and 0.1 dB. They are less than the instrumental errors of the experiment (2 dB).

[35] The experimental results were also compared to the calculation estimates obtained for the corresponding conditions by the Kazantsev–Smith [*Aparina et al.*, 1972] and *International Radio Consultative Committee (CCIR)* [1982] methods. The calculations led to controversial results. The Kazantsev–Smith method gave the values of the field strength below the measured values on the average by 8.2 and 4.6 dB in the periods of maximum and minimum solar activity, respectively. In the CCIR method, vice versa, the calculated values stably exceed the observed values. For the maximum and minimum of solar activity the discrepancy was on the average 4.8 and 3.1 dB, respectively.

[36] Thus a correct analysis of the experimental data showed that at midlatitude paths with the length less than 500 km, the main mechanism of attenuation of HF waves is the collision absorption which is fairly reliably evaluated using the gas-kinetic model of $\nu_e(h)$.

[37] The contradictions revealed in the VS and OS experiments (at different frequencies relative to the MUF) gave rise to the development of the theory of the electromagnetic emission transfer taking into account the multiple small-angle scattering in the randomly irregular magneto-active plasma. [*Bronin and Zabotin,* 1992]. Application of this theory to calculations of the reflected by the plane ionosphere electromagnetic emission of point-like source revealed an important feature. As a result of the scattering much more energy leaves the ray tube formed by the rays close to the vertical than comes in from the adjacent ray tubes. [*Zabotin et al.,* 1998]. At measurements of the HF wave absorption by the A1 method this deficit is manifested in the additional collisionless attenuation. At a distance of about 100 km from the transmitter the effect becomes negligible. Currently, this point of view is confirmed by the results of the field strength measurements at frequencies below MUF and makes it possible to improve the agreement between the A1 experimental data and the theory [*Bronin et al.,* 1999].

[38] It is worth noting that the conclusions based on the experiment results provided a base for the creation of the HF channel model [*Barabashov and Anishin,* 2002; *Barabashov and Vertogradov*, 1996, 2000; *Barabashov et al.*, 2001] and development of new approaches to their imitation simulation [*Vertogradov*, 2003; *Vertogradov and Mineev,* 2003]. During recent years the imitation model of the ionospheric HF channel was thoroughly tested experimentally at midlatitude paths of various orientation and length from 1000 to 6500 km [*Vertogradov et al.,* 2004]. Modeling the radio signal prop-

agation, the following principal statements are used. The mean field is determined as a result of incoherent summation of the fields of all possible rays in the reception point taking into account multiple propagation modes and antenna parameters.

[39] The number of rays and their parameters are determined using the geometry-optical approximation on the basis of the solution of the eichannel equation solution and transfer with allowance for the magnetic field of the Earth.

[40] The calculated signal characteristics at the reception point are: the field strength, arrival angles, group and phase paths, collision absorption, spatial attenuation, losses due to the reflection from the ionospheric E_s layer, losses at the reflection from the Earth for multiple propagation modes, and polarization discordance. The propagation medium is taken corrected by VS data using the IRI model of spatial distribution of the electron concentration. [*Bilitza*, 2001, 2002] and by the effective electron collision frequency. The partial collision frequencies with neutrals are calculated using the MSIS model of the neutral atmosphere and scattering cross sections [*Banks*, 1966; *Gurevich and Shvartsburg*, 1973]. The electron temperature and geomagnetic field parameters are also chosen according to the IRI model.

8. Conclusions

[41] The gas-kinetic estimates of the effective electron collision frequency adequately describe the HF wave absorption in the midlatitude ionosphere [*Barabashov et al.*, 1997; *Benediktov and Tolmacheva*, 1975; *Skrebkova*, 1975]. The estimates need improvement only in the sense of specification of the cross sections of electrons at atmospheric constituents and models of their concentration and electron temperature.

[42] The discrepancy between the gas-kinetic values of the collision frequencies in the E region and empirical estimates obtained in the early experiments [*Aggarwal et al.*, 1979; *Setty*, 1972; *Thrane and Piggott,* 1966] are caused by the errors in determination of the virtual heights [*Vodolazkin et al.,* 1989a]. Similar discrepancies in the ionospheric F region manifest the presence of additional collisonless mechanisms of radio wave attenuation. The mechanisms may be dissipative or nondissipative.

[43] An essential role is played by the nondissipative mechanism: small-angle scattering at electron concentration irregularities. At the ground-based sounding of the ionosphere this scattering leads to such redistribution of the reflected emission which gives an energy deficit in the vertical direction [*Zabotin et al.,* 1998]. At the oblique propagation in the vicinity of MUF the scattering leads to outgoing of the emission into the topside ionosphere [*Beley et al.*, 1990; *Bronin et al.*, 1991]. The scattering does not play any significant role at the reception of the signals of space sources at middle latitudes when the coherent and incoherent components of the emission pass the ionosphere [*Benediktov and Tolmacheva*, 1975; *Skrebkova*, 1975]. Neither influence the scattering the intensity of the emission at the oblique sounding at frequencies below MUF when both emission components come to the observation point [*Barabashov et al.,* 1997].

[44] Two mechanisms of dissipative losses are revealed. One mechanism is observed in the A2 method data in the high-latitude ionosphere and is explained by the interaction of radio waves with the developed plasma turbulence [*Berezhko et al.*, 1987; *Gel'berg et al.,* 1985]. (The nature of the extra attenuation of the radioemission of space sources in the low-latitude ionosphere is not yet known.) The second mechanism is anomalous absorption of "o" waves caused by their statistical transformation into "z" waves [*Denisenko et al.*, 1987a, 1987b; *Vodolazkin et al.*, 1989a, 1989b]. As mentioned above, one of the arguments in favor of its existence is the observation of diffusive traces at topside ionograms in the frequency range from $f_{\max}$ to f_{UHF} [*Denisenko et al.*, 1987a, 1987b, 1993]. However, recently an alternate explanation (scattering of "z" waves) was proposed [*Zabotin et al.*, 1997]. So direct observation of the transformation effect presents an obvious interest. This can be realized in special experiments on transionospheric sounding receiving pulse signals of ground-based transmitters on board a satellite orbiting below the ionospheric maximum [*Denisenko et al.*, 2000].

[45] On the basis of the results of the study a model of HF signal propagation in the ionospheric plasma was developed [*Barabashov and Anishin*, 2002; *Barabashov and Vertogradov*, 1996, 2000; *Barabashov et al.,* 2001; *Vertogradov*, 2003; *Vertogradov and Mineev*, 2003].

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