SPORADIC-*E* PLASMA IRREGULARITIES UNDER INTENSIFICATION OF TURBULENT MIXING

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ABSTRACT

The effect of intensification of turbulent mixing on the sporadic-*E* plasma irregularities is considered in this work. The consideration is based on three-fluid description of ionospheric plasma. In the framework of this description an analytic expression for estimation of level of plasma density fluctuations generated by the neutral turbulence in sporadic-*E* is derived. The expression takes dependence of the sporadic-*E* thickness on turbulent mixing intensity into account. Using the formula, it is shown that intensification of turbulence has to decrease the level of plasma density fluctuations in the layer. The decrease of the fluctuation level is explained by an increase in the sporadic-*E* thickness (decrease in the local gradient of mean plasma density) due to turbulent mixing.

1. INTRODUCTION

Atmospheric turbulence plays an important role in the dynamics of the lower ionosphere. Sources of the turbulence above an altitude of 80 km are destruction of the atmospheric gravity waves and tides propagating from the lower atmospheric layers and also the nonlinear interaction of planetary waves and tides [1]. These large-scale atmospheric motions are also responsible for a vertical shear in the neutral wind that is necessary for the production of mid-latitude-type sporadic-*E* [1-7] (such layers are also observed at auroral latitudes [8-10] and even near the magnetic equator [5]). Sporadic-*E* (E_s) is a thin layer of enhanced ionisation in the *E*-region ionosphere. The mechanism of E_s formation is explained by wind-shear theory [3, 5, 11]. According to the theory the E_s layer results from the interaction of plasma embedded in the neutral wind with the geomagnetic field under appropriate vertical profile of the horizontal wind velocity. The sporadic-*E* ion composition differs from that of the normal *E*-region. The ions in the layer are metallic such as Fe^+ and Mg^+ with a very slow recombination reaction [3, 5, 9, 12]. It is known [3, 5, 13] that atmospheric turbulence exerts an essential influence on the E_s layer if its height is below the homopause. The homopause (or turbopause) can be defined as the level where the energy dissipation by molecular processes becomes larger than that of turbulent processes [14]. At the homopause, mixing stops and diffuse separation sets in. The turbulence defines both mean characteristics and fine structure of the layer. Intensification of the turbulence reduces the peak amplitude of the layer and increases the E_s thickness [13].

The aim of this work is to consider theoretically possible effect of intensification of turbulent mixing on sporadic-*E* plasma irregularities.

2. BASIC ASSUMPTIONS AND EQUATIONS

The *E*-region of ionosphere is low temperature, multi-component, collisional plasma. In many cases it may be considered as three-component one and described by a three-fluid model: (1) electrons with number density N_e, mass m_e, temperature T_e, and velocity $\mathbf{v}_e$, (2) ions with N_i, mean (effective) mass m_i, T_i, and $\mathbf{v}_i$, and (3) neutrals with N_n, mean mass m_n, T_n, and $\mathbf{U}$. In the lower ionosphere the assumptions of quasi-neutrality, $N_e=N_i=N$, and isothermality $T_e=T_i=T_n=T$ are valid. At the altitudes of interest, collisions between the electrically charged particles and neutrals dominate; Coulomb collisions do not play a significant role because the gas is weakly ionized $N_n>>N$. Usually the neutral gas may be considered as an incompressible one:

$$\nabla\cdot\mathbf{U}=0. \tag{1}$$

The charged particles have no essential influence on the motion of neutral gas in the lower ionosphere, and their behaviour may be described by the continuity and momentum equations for electrons and ions under the given velocity field of the gas $\mathbf{U}(\mathbf{x}, t)$ [3]

$$\partial N/\partial t + \nabla\cdot(N\mathbf{v}_e) = 0\,, \tag{2}$$

$$\partial N/\partial t + \nabla\cdot(N\mathbf{v}_i) = 0\,, \tag{3}$$

$$-e\mathbf{E}/m_e - \omega_{Be}(\mathbf{v}_e\times\mathbf{b}) - v_{Te}^2\,\nabla N/N = (\mathbf{v}_e-\mathbf{U})/\tau_e\,, \tag{4}$$

$$e\mathbf{E}/m_i + \omega_{Bi}(\mathbf{v}_i\times\mathbf{b}) - v_{Ti}^2\,\nabla N/N = (\mathbf{v}_i-\mathbf{U})/\tau_i\,, \tag{5}$$

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where **E** is the electric field, $\omega_{Be,i}$ is the electron (ion) gyro frequency, $v_{Te,i}$ is the thermal velocity of electrons (ions), **b**=**B**/B is the unit vector along the geomagnetic field **B,** $\tau_{e,i}$ is a mean time between collisions of electrons (ions) with neutrals.

The use of Eqs. 2-5 indicates that we consider slow process both in space and in time: the time-scale is much larger than τ_i, and the length-scale much larger than an ion mean free path Λ_i. That is why both the electron and ion inertia are neglected in the momentum equations Eqs. 4-5. If the only electric field **E** considered is that required to prevent charge separation (due to **E** electrons tend to follow ions), and eliminating **E** from Eqs. 4-5, we then obtain the local drift velocity of ions (or plasma in general):

$$\mathbf{v}_i(\mathbf{x},t) \approx \mathbf{U}(\mathbf{x},t) + \beta_i(\mathbf{U}\times\mathbf{b}) - D_A\nabla^2 N\,, \qquad (6)$$

here $\beta_i=\omega_{Bi}\tau_i$, D_A is the ambipolar diffusion coefficient.

Substitution of Eq. 6 in Eq. 3 gives the relation between N and **U**

$$\partial N/\partial t + \nabla\cdot(N\mathbf{U}) + \beta_i\mathbf{b}\nabla\times(N\mathbf{U}) - D_A\nabla^2 N = 0\,. \quad (7)$$

Eq. 7 describes the behaviour of N when plasma is embedded in the flow of neutral gas.

3. GOVERNING EQUATION FOR PLASMA-DENSITY FLUCTUATIONS

In a turbulent flow of gas, **U** and N can be divided into their ensemble mean parts $\mathbf{u}_0$=<**U**>, N_0=<N> (the angle brackets indicate an ensemble average) and fluctuations around them **u**, N_1: $\mathbf{U}=\mathbf{u}_0+\mathbf{u}$ ($\mathbf{u}_0>\mathbf{u}$, $\langle\mathbf{u}\rangle=0$), and $N=N_0+N_1$ ($N_0>N_1$, $\langle N_1\rangle=0$). The length-scales of random ingredients **u** and N_1 have to be close to each other and smaller than the length-scales of mean quantities $\mathbf{u}_0$ and N_0. The same is valid for the time-scales. If l is the length-scale of random fluctuations, L_0 stands for the length-scale of $\mathbf{u}_0$, and $L_N=N_0|\nabla N_0|^{-1}$ is the length-scale of gradient in N_0, then evidently the following inequalities are valid: $l< L_N\le L_0$.

Restricting the consideration to length-scales that belong to an inertial range of turbulence (in this range the random velocity field is homogeneous and isotropic), and using Eq. 7, we can write the governing equation for the relative plasma-density fluctuations, $\delta N=N_1/N_0$ (for details see [15]):

$$\partial\delta N/\partial t + \nabla\cdot(\delta N\mathbf{u}) - D_A\nabla^2\delta N$$

$$= -L_N^{-1}(\mathbf{u}\cdot\mathbf{n}) - \beta_i\mathbf{b}\nabla\times\mathbf{u}\,, \qquad (8)$$

where $\mathbf{n}=L_N\nabla N_0/N_0$ is the unit vector along the gradient in N_0.

Formation of fluctuations δN in turbulent flow of ionospheric gas is described by Eq. 8. The process in which the neutral gas turbulence in conjunction with a background electron-density gradient produce plasma irregularities by mixing regions of high and low density is described by the first term on the right-hand side of Eq. 8, this term is more important at larger scales, $l>\beta_i L_N$; the second dominates at smaller ones, $l<\beta_i L_N$, and represents the interaction of plasma embedded in turbulent motions of neutral gas with the magnetic field.

Under the assumption of statistical homogeneity and stationarity of the random fields $\mathbf{u}(\mathbf{x}, t)$ and $\delta N(\mathbf{x}, t)$, the space-time Fourier transform of Eq. 8 is

$$(D_A k^2 - i\omega)\delta N(\mathbf{k},\omega) + ik_j\int d\mathbf{k}'d\omega'\delta N(\mathbf{k}',\omega')u_j(\mathbf{k}'',\omega'')$$

$$= -L_N^{-1}(\mathbf{n}\cdot\mathbf{u}(\mathbf{k},\omega)) - i\beta_i\mathbf{k}(\mathbf{u}(\mathbf{k},\omega)\times\mathbf{b})\,, \qquad (9)$$

where $\mathbf{k}''=\mathbf{k}-\mathbf{k}'$, $\omega''=\omega-\omega'$.

The convolution term on the left-hand side of Eq. 9 represents the contribution of mode interactions in the process of plasma fluctuation generation. Taking it into account through the coefficient of turbulent diffusion, D_T, we immediately obtain

$$\delta N(\mathbf{k},\omega) = \frac{-L_N^{-1}\mathbf{n} - i\beta_i(\mathbf{b}\times\mathbf{k})}{(D_A + D_T)k^2 - i\omega}\cdot\mathbf{u}(\mathbf{k},\omega)\,. \qquad (10)$$

According to the Richardson–Obukhov law [16] that describes the turbulent diffusion caused by eddies with length-scales smaller than $l=k^{-1}$:

$$D_T(l) = C_T\varepsilon^{1/2}l^{3/4}\,, \qquad (11)$$

here $C_T\approx1$ is a dimensionless constant, ε is the mean rate of turbulent energy dissipation per unit mass.

4. LEVEL OF THE PLASMA FLUCTUATIONS GENERATED BY NEUTRAL TURBULENCE

For statistically homogeneous and stationary random fields $\mathbf{u}(\mathbf{k}, \omega)$ and $\delta N(\mathbf{k}, \omega)$ the following relations are valid

$$\langle \delta N(\mathbf{k},\omega)\cdot \delta N^{*}(\mathbf{k}',\omega')\rangle = \Psi(\mathbf{k},\omega)\delta(\mathbf{k}'')\delta(\omega''), \quad (12)$$

$$\langle \mathbf{u}_{\alpha}(\mathbf{k},\omega)\cdot \mathbf{u}^{*}_{\beta}(\mathbf{k}',\omega')\rangle = \Phi_{\alpha\beta}(\mathbf{k},\omega)\delta(\mathbf{k}'')\delta(\omega''), \quad (13)$$

where $\mathbf{k}''=\mathbf{k}-\mathbf{k}'$, $\omega''=\omega-\omega'$, the (*) denotes a complex conjugate, $\Psi(\mathbf{k}, \omega)$ is the spatiotemporal spectrum of δN, $\Phi_{\alpha\beta}(\mathbf{k}, \omega)$ is spectrum tensor of $\mathbf{u}$, in the inertial range (under assumption of exponential decorrelation of the turbulent velocity field in time) it takes the form

$$\Phi_{\alpha\beta}(\mathbf{k},\omega) = \frac{D_{\alpha\beta}(\mathbf{k})\omega_k E(k)}{4\pi^2 k^2(\omega^2+\omega_k^2)} \quad (k_0 < k < k_\nu), \quad (14)$$

here $D_{\alpha\beta}(\mathbf{k})=\delta_{\alpha\beta}-k_\alpha k_\beta k^{-2}$ is the projection operator, $\omega_k=\varepsilon^{1/3}k^{2/3}+\nu k^2$ is the characteristic frequency of eddy with a length-scale k^{-1},

$$E(k) = C_1 \varepsilon^{2/3} k^{-5/3} \quad (15)$$

is the energy spectrum function, the Kolmogorov constant C_1 is around 1.5, $k_0^{-1}=L_0$ is the basic energy input scale,

$$k_\nu = (\varepsilon/\nu^3)^{1/4} \quad (16)$$

is the Kolmogorov dissipation wavenumber, ν is the kinematic viscosity of the gas [17, 18].

Using Eqs. 9-12 we obtain $\Psi(\mathbf{k}, \omega)$

$$\Psi(\mathbf{k},\omega) = \frac{L_N^{-2}k^{-2}(\mathbf{n}\times\mathbf{k})^2 + \beta_i^2(\mathbf{b}\times\mathbf{k})^2}{4\pi^2 k^2(\omega^2+\Omega_k^2)(\omega^2+\omega_k^2)}\cdot \omega_k E(k), \quad (17)$$

here $\Omega_k=(D_A+D_T)k^2=D_A k^2+\varepsilon^{1/3}k^{2/3}$.

Now we may derive an expression for mean-square level of plasma density fluctuations generated by neutral turbulence in the lower ionosphere and sporadic-E. It is known that three-dimensional (3D) spectrum of δN is related with $\Psi(\mathbf{k}, \omega)$ as

$$P(\mathbf{k}) = \int_{-\infty}^{\infty} d\omega \Psi(\mathbf{k},\omega). \quad (18)$$

After integration, we have the 3D spectrum of δN

$$P(\mathbf{k}) = \frac{L_N^{-2}k^{-2}(\mathbf{n}\times\mathbf{k})^2 + \beta_i^2(\mathbf{b}\times\mathbf{k})^2}{4\pi k^2 \Omega_k(\omega_k+\Omega_k)}\cdot E(k). \quad (19)$$

Using Eq. 19, the mean-square fluctuation level in the range, $k_1 \le k \le k_2$, can be calculated

$$\langle \delta N^2\rangle = \int d\mathbf{k}P(\mathbf{k}) = \int_{k_1}^{k_2} dk P_0(k), \quad (20)$$

where

$$P_0(k) = \frac{(L_N^{-2}+\beta_i^2 k^2)(1+(k/k_d)^{4/3})^{-1}}{k^3(2+(k/k_d)^{4/3}+(k/k_\nu)^{4/3})} \quad (21)$$

is the omnidirectional spectrum of δN,

$$k_d = (\varepsilon/D_A^3)^{1/4} \quad (22)$$

is the Obukhov-Corrsin wavenumber [18], at which (in our case) dissipation of the plasma fluctuations due to ambipolar diffusion is equal to the turbulent dissipation.

Integration in Eq. 20 gives a formula for the root-mean-square (rms) level of δN

$$\langle \delta N^2\rangle^{1/2} = [S(k_2/k_d) - S(k_1/k_d)]^{1/2}, \quad (23)$$

here

$$S(x) = \frac{3}{8}L_N^{-2}k_d^{-2}x^{-2}\left[(3+\mathrm{Sc})x^{4/3} - 2/3\right] + \frac{3}{2}\frac{L_N^{-2}k_d^{-2}}{1-\mathrm{Sc}}\left[\arctan x^{2/3} - \left(\frac{1+\mathrm{Sc}}{2}\right)^{5/2}\arctan\frac{x^{2/3}(1+\mathrm{Sc})^{1/2}}{2^{1/2}}\right] + \frac{3}{8}\frac{\beta_i^2}{1-\mathrm{Sc}}\left[2\ln\frac{x^{4/3}}{1+x^{4/3}} - (1+\mathrm{Sc})\ln\frac{x^{4/3}(1+\mathrm{Sc})}{x^{4/3}(1+\mathrm{Sc})+2}\right] \quad (24)$$

where $\mathrm{Sc}=\nu/D_A$ is the Schmidt number.

5. SPORADIC-*E* THICKNESS AND PEACK AMPLITUDE

Sporadic-E thickness and plasma density in its peak (peak amplitude) are important parameters of the layer. They can be measured during rocket experiments [2, 5-10] and calculated theoretically [3, 11, 13]. If sporadic-E is above the turbopause level and its formation results from an action of a sinusoidal wave of neutral wind with amplitude u_0 and vertical wavelength L_0, then the sporadic-E peak amplitude N_{00} is [3]

$$N_{00} = N_E \sqrt{u_0 L_0 \beta_i \cos I / D_A}\ , \qquad (25)$$

where N_E is the plasma density in the background E-region, I is the magnetic dip angle. In this case the E_s thickness is

$$L_{s0} = \sqrt{D_A L_0 / (u_0 \beta_i \cos I)}\ . \qquad (26)$$

It is known [3, 13] that atmospheric turbulence is very important for existence of sporadic-E below the turbopause. Intensification of turbulent mixing may result in broadening of the layer and falling of its peak so much that it disappears into the background E-region. For the E_s layer below turbopause the coefficient of turbulent diffusion, D_T, has to be used instead of D_A in Eqs. 25-26 (l=L_s in Eq. 11 for D_T) and then the plasma density in the E_s peak and the E_s thickness become

$$N_0 = 2\pi N_E \left(\frac{u_0^3 \beta_i^3 \cos^3 I}{\varepsilon L_0} \right)^{1/2}, \qquad (27)$$

$$L_s = \frac{\varepsilon^{1/2} L_0^{3/2}}{(2\pi u_0 \beta_i \cos I)^{3/2}}\ . \qquad (28)$$

The mean rate of turbulent energy dissipation ε is fundamental parameter of turbulence and reflects an intensity of turbulent mixing. From Eq. 27 one can see that plasma density in the sporadic-E maximum has to decrease with intensification of turbulent mixing, $N_0 \propto \varepsilon^{-1/2}$. Whereas according to Eq. 28, the E_s thickness increases with intensity of turbulence, $L_s \propto \varepsilon^{1/2}$. The rate ε at which the E_s layer has to disappear can be defined from Eq. 27; the condition is N_0=N_E, the plasma density in the E_s peak becomes equal to the density in the background E-region, and then

$$\varepsilon_{\max} = 4\pi^2 (u_0 \beta_i \cos I)^3 L_0^{-1}\ . \qquad (29)$$

6. NUMERICAL ANALYSIS

To analyse an effect of turbulent mixing intensification on the level of sporadic-E plasma fluctuations, Eqs. 23-24 can be used. We assume that the length-scale of local gradient in the mean plasma density of the layer $L_N \approx L_s$ (Eq. 28), then Eq. 24 takes the form

$$S(x) = \frac{3}{8} \frac{(2\pi u_0 \beta_i \cos I)^3}{\varepsilon L_0^3 k_d^2 x^2} \left[(3+\mathrm{Sc}) x^{4/3} - 2/3 \right]$$
$$+ \frac{3}{2} \frac{(2\pi u_0 \beta_i \cos I)^3}{\varepsilon L_0^3 k_d^2 (1-\mathrm{Sc})} \left[\arctan x^{2/3} - \left(\frac{1+\mathrm{Sc}}{2} \right)^{5/2} \arctan \frac{x^{2/3}(1+\mathrm{Sc})^{1/2}}{2^{1/2}} \right]$$
$$+ \frac{3}{8} \frac{\beta_i^2}{1-\mathrm{Sc}} \left[2 \ln \frac{x^{4/3}}{1+x^{4/3}} - (1+\mathrm{Sc}) \ln \frac{x^{4/3}(1+\mathrm{Sc})}{x^{4/3}(1+\mathrm{Sc})+2} \right]. \qquad (30)$$

To estimate the level of sporadic-E plasma fluctuations, we consider the layer in the mid-latitude ionosphere (magnetic dip angle I=45°) near altitude h=100 km. For the calculations, values of relevant parameters are taken from [2, 4, 6, 12, 19] and given in Tabs. 1-2 (two cases of the sporadic-E ion composition are considered when the mean ion mass, m_i, took values 31 and 51 a.m.u., the last m_i, if concentration of Fe^+ is about 80% [12]).

Table 1. Basic ionospheric and neutral gas parameters

N_E m^{-3}	T °K	τ_i s	ν m^{2}s^{-1}	L_0 km	u_0 m/s
2×10^9	210	3.3×10^{-4}	20.7	10	70

Table 2. Plasma parameters for the two cases of sporadic-E ion composition

m_i a.m.u.	ω_{Bi} s^{-1}	β_i=$\omega_{Bi}\tau_i$	D_A m^{2}s^{-1}	Sc=ν/D_A
31	150	0.05	37.3	0.55
51	90	0.03	22.7	0.91

Using Eq. 29, an intensity of turbulent mixing (the dissipation rate ε_{max}), at which the layer has to vanish in the background E-region can be obtained. For the plasma density in the E-region N_E =2×10^9 m^{-3}, the E_s peak has to disappear at ε_{max}=60.0 mW/kg, if β_i=0.05, and at ε_{max}=12.9 mW/kg, if β_i=0.03.

From Eq. 23 and Eq. 30 one can show that if ε changes from 5 to 10 mW/kg for the first ion composition and plasma irregularities with length-scales smaller than 200 m, the rms fluctuation level δN decreased from 7.2% to 5.9% of N_0, background plasma density in the layer (see Tab. 3 and Fig. 1), and in the second case from 3.9% to 3.2% (see Tab. 4 and Fig. 2).

Tabs. 3-4 present results of calculation of parameters of E_s layer and plasma irregularities generated in the layer by the neutral gas turbulence for the two cases of ion composition under intensification of turbulent mixing: the plasma density N_0 in the E_s peak, Eq. 27, the E_s thickness L_s, Eq. 28, the Obukhov-Corrsin length-scale k_d^{-1} (the smallest size of the irregularities), Eq. 22, and rms level of relative fluctuations, $\delta N = N_1/N_0$, in the E_s plasma density, Eq. 23 and Eq. 30.

Table 3. Calculated sporadic-E and plasma irregularities parameters for m_i=31 a.m.u.

ε mW/kg	N_0 m^{-3}	L_s km	k_d^{-1} m	$<\delta N^2>^{1/2}$ %
5	6.9×10^9	1.15	56.8	7.2
6	6.3×10^9	1.26	54.3	6.8
7	5.8×10^9	1.36	52.2	6.5
8	5.5×10^9	1.46	50.5	6.2
9	5.2×10^9	1.55	49.0	6.0
10	5.9×10^9	1.63	47.7	5.9

Table 4. Same as Tab.3 but for m_i=51 a.m.u.

ε mW/kg	N_0 m^{-3}	L_s km	k_d^{-1} m	$<\delta N^2>^{1/2}$ %
5	3.2×10^9	2.48	39.1	3.9
6	2.9×10^9	2.72	37.3	3.7
7	2.7×10^9	2.94	35.9	3.5
8	2.5×10^9	3.14	34.8	3.4
9	2.4×10^9	3.33	33.7	3.3
10	2.3×10^9	3.51	32.9	3.2

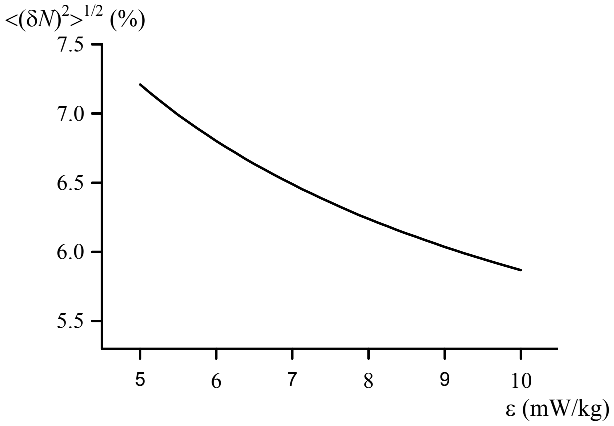

Figure 1. Dependence of rms level of sporadic-E plasma fluctuations on ε for m_i=31 a.u.m.

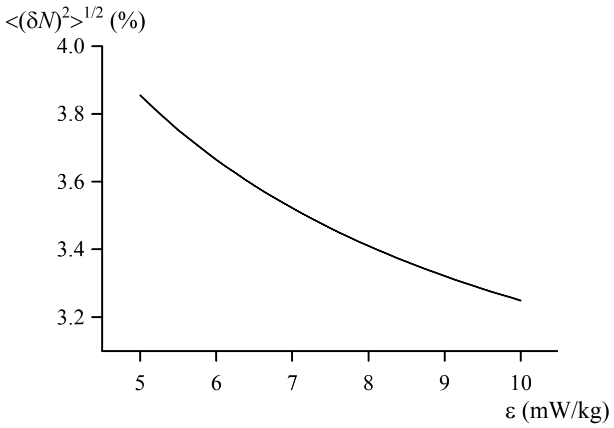

Figure 2. Same as Fig. 1 but for m_i=51 a.u.m.

The decrease of the fluctuation level with intensification of turbulent mixing (see Figs. 1-2) is explained by increasing of sporadic-*E* thickness L_s from 1.15 to 1.63 km in the first case of ion composition and from 2.48 to 3.51 km in the second (see Tabs. 3-4), and hence decreasing the local plasma density gradient which is important for generation of the plasma irregularities in the layer. Calculation of plasma density in the E_s peak shows decrease in N_0 from 6.9×10^9 to 4.9×10^9 m^{-3} under intensification of turbulent mixing for the first ion composition, β_i=0.05 (see Tab. 3), and from 3.2×10^9 to 2.3×10^9 m^{-3} for the second, β_i=0.03 (see Tab. 4).

7. CONCLUSION

The results of present work have shown that intensification of turbulent mixing has a notable influence on sporadic-*E* layer and its irregular structure. Intensity of the sporadic-*E* plasma irregularities has to decrease with enhancement of the neutral gas turbulence. The obtained results can be tested by rocket or, more likely, combined rocket-radar experiments that measure simultaneously the winds, turbulence, sporadic-*E* parameters and plasma irregularities.

It should be noted that Eq. 19, the 3D spectrum of plasma density fluctuations, can be used to derive expressions for the radar scattering cross-section and the one-dimensional spectrum which could be measured along the given direction.

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