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IONOSPHERIC IRREGULARITIES INDUCED BY THE TURBULENCE OF THE NEUTRAL ATMOSPHERE: POSSIBLE DEVIATION FROM ISOTROPY

Yu. V. Kyzyurov

Main Astronomical Observatory NASU, Kyiv-127, 03680, Ukraine

The results of study of possible deviation of plasma irregularities caused by the action of neutral air turbulence in the lower ionosphere from isotropy are presented in this report. The consideration was based on an analytic expression for the three-dimensional (3D) spectrum of such irregularities. By integrating the 3D spectrum, 1D spectra were derived for two different directions of its possible measurements. It was shown that the spectra of the irregularities are quite close to an isotropic one, although there are some their deviations from isotropy on the edges of the considered wave-number range. These deviations result from changes in a relative role of the geomagnetic field (more important for larger wave numbers) and the gradient of mean plasma density (more important for smaller ones) in creating the plasma irregularities of different scales. Estimations of slope of the irregularity spectra and of the root-mean-square level of plasma fluctuations were made too. There is good agreement between the obtained results and the data gathered during a rocket-radar simultaneous experiment in the lower ionosphere at high latitudes.

INTRODUCTION

Radar and rocket observations at various latitudes show that plasma irregularities are created as a consequence of the action of neutral air turbulence in the lower ionosphere [4—6]. It is generally assumed that such irregularities are isotropic or at least quasi-isotropic, in contrast to field-aligned ionospheric irregularities generated by current-driven plasma instabilities in the ionosphere. The isotropy of the ionospheric irregularities results in the weak aspect sensitivity of radar returns (whilst the field-aligned irregularities provide the strong aspect sensitivity). It is evident that an isotropy of irregularities results in the isotropy of their spectrum. It means in turn that experimental spectra of the irregularities that are measured during rocket flights and by ground-based radar instruments must be the same. In the case of quasi-isotropic irregularities certain difference between these experimental spectra must exist. The purpose of this report is to investigate possible deviation of the plasma irregularities caused by neutral turbulence from isotropy by comparing irregularity spectra, which can be measured in vertical and horizontal directions. An understanding of features of the deviation is needed not only for the general understanding of the nature of irregularities in the lower ionosphere but also for the better understanding of observational results obtained during combined rocket and radar experimental campaigns.

ONE-DIMENSIONAL SPECTRA OF PLASMA IRREGULARITIES

To study the deviation from isotropy for ionospheric irregularities caused by mixing of plasma resulting from the action of turbulence in the neutral atmosphere, we use an analytic expression for the three-dimensional (3D) spectrum of the irregularities which was recently obtained in the following form [2]:

$$P(k) = \Omega(k)\cdot[L_{\mathrm{N}}^{-2}k^{-2}(\mathbf{n}\times\mathbf{k})^2+\beta_{\mathrm{i}}^2(\mathbf{b}\times\mathbf{k})^2]\cdot C_1\varepsilon^{2/3}k^{-11/3}, \qquad L_{\mathrm{N}}^{-1}<k<k_{\mathrm{d}}, \tag{1}$$

$$\Omega^{-1}(k) = 4\pi(\varepsilon^{1/3}k^{2/3} + 2\alpha_r N_0 + D_A k^2)[2\varepsilon^{1/3}k^{2/3} + 2\alpha_r N_0 + (D_A + \mu_n)k^2],$$

where $n = L_N N_0^{-1}\nabla N_0$ is the unit vector along the gradient of mean plasma density N_0 with a length scale L_N, $\mathbf{b} = \mathbf{B}/B$ is the unit vector along the geomagnetic field $\mathbf{B}$, $\beta_i = \omega_{Bi}/\nu_i$ is the ratio of the ion gyrofrequency, $\omega_{Bi} = eB/m_i c$, to ion-neutral collision frequency, ν_i, C_1 is a dimensionless constant of order unity, ε is the rate of dissipation of turbulent energy, α_r is the recombination coefficient, D_A is the ambipolar diffusion coefficient, μ_n is the kinematic viscosity of neutral gas (in our case $\mu_n \approx D_A$), and $k_d \approx (\varepsilon/\mu_n^3)^{1/4}$ is the Kolmogorov dissipation wave number. The expression (1) is valid when: the neutral turbulence is usual fluid turbulence of the Kolmogorov type, the plasma component has no influence on turbulent movements of neutrals, and a vertical gradient of background plasma density is insufficient for the excitation of plasma instability.

With the use of (1) estimates of the root-mean-square (rms) level of relative plasma-density fluctuations, $\langle\delta N^2/N_0^2\rangle^{1/2}$, have been made in the case of the mid-latitude ionosphere

$$\frac{\langle\delta N^2}{N_0^2\rangle} = \int d\mathbf{k}P(\mathbf{k}) = \int_{k_1}^{k_2} dkP_1(k) \tag{2}$$

with

$$P_1(k) = \frac{8\pi}{3}\Omega(k)(L_N^{-2} + \beta_i^2 k^2)C_1\varepsilon^{2/3}k^{-5/3}. \tag{3}$$

A good agreement with experimental data was found [3]. Shapes of 1D spectra predicted by 1D power spectral density (PSD), (3) was also consistent with experimental spectra. It means that the plasma irregularities induced by neutral turbulence are really very close to quasi-isotropic ones, though the 3D spectrum is not quite isotropic because of its dependence on **n** and **b**.

Using the 3D spectrum, (1) 1D spectrum that can be measured along z-direction in experiments is easily obtained:

$$S_1(k_z) = \int_0^{\sqrt{k_d^2-k_z^2}} k_\perp dk_\perp \int_0^{2\pi} P(\mathbf{k}d\varphi.$$

In the case of *in situ* rocket experiments we will regard that the 1D spectrum, $S_1'(k_z)$, is measured along the mean plasma density gradient (vertical direction), **z** || **n**, and then

$$S_1'(k_z) = C_1\pi\varepsilon^{2/3} \int_0^{\sqrt{k_d^2-k_z^2}} \Omega(k)[2L_N^{-2}k_\perp^2 + \beta_i^2 k^2(k_\perp^2 + k_\perp^2\cos^2\theta + 2k_z^2\sin^2\theta)]k^{-17/3}k_\perp dk_\perp, \tag{4}$$

here $k^2 = k_\perp^2 + k_z^2$, $\theta = 90° - I$ is an angle between **b** and **n**, I is the magnetic dip angle ($I \approx 80°$ is chosen in the present case).

In the case of ground-based measurements **z** coincides with the drift direction of the irregularities, which is most commonly eastward (horizontal direction), i.e., **z** ⊥ both **n** and **b**, and the 1D spectrum, $S_1''(k_z)$, is

$$S_1''(k_z) = C_1\pi\varepsilon^{2/3} \int_0^{\sqrt{k_d^2-k_z^2}} \Omega(k)(L_N^{-2} + \beta_i^2 k^2)(k_z^2 + 2k_\perp^2)k^{-17/3}k_\perp dk_\perp. \tag{5}$$

To illustrate possible deviation of the irregularity spectrum from isotropy, the following set of values of relevant parameters which are quite realistic for the high-latitude lower ionosphere (the height range of 90—95 km) are taken: $L_N \sim 10^4$ m, $N_0 \sim 4\cdot 10^{10}$ m^{-3}, $\beta_i \approx 0.01$, $D_A \approx \mu_n \sim 4$ m^{2}s^{-1}, $\varepsilon \sim 0.1$ m^{2}s^{-3}, $\alpha_r \sim 3.8\cdot 10^{-13}$ m^{3}s^{-1}, $I \approx 80°$ [5, 7, 8]. Figure 1 shows the normalized 1D spectra for the chosen set of

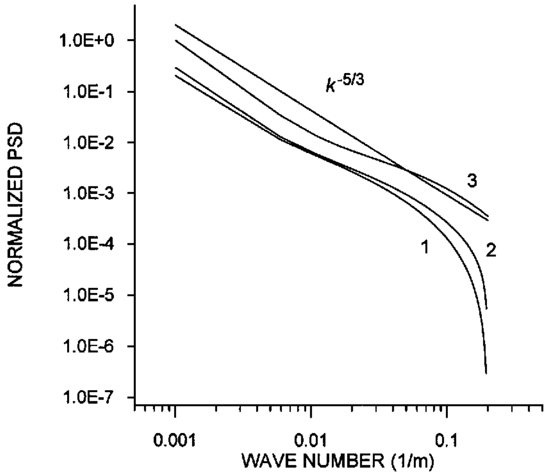

Figure 1. Normalized 1D spectra (or PSD) of relative plasma-density fluctuations predicted by (4), (5), and (3): line 1 represents $S_1(k_z)/P_1(k_1)$ ($k_1 = 10^{-3}$ m^{-1}), line 2 — S_1 $(k_z)/P_1(k_1)$, line 3 — $P_1(k)/P_1(k_1)$ straight line represents the slope of the Kolmogorov spectrum

values of parameters: line 1 represents the case of measurement in the vertical direction, $S_1'(k_z)/P_1(k_1)$ ($k_1 = 10^{-3}$ m^{-1}) (see (4)), line 2 corresponds to the case of the horizontal direction, $S_1''(k_z)/P_1(k_1)$ (see (5)), line 3 is for $P_1(k)/P_1(k_1)$ (see (3)), the case of isotropic irregularities, and the straight line represents the slope of Kolmogorov spectrum, $k^{-5/3}$. It is seen that the spectra of the irregularities are quite close to an isotropic one, though there are some their deviations from isotropy on the edges of the considered wave-number range. These deviations result from changes in a relative role of the geomagnetic field (more important for larger wave numbers) and of the gradient of mean plasma density (more important for smaller wave numbers) in creating the plasma irregularities of different scales. The spectral form $S_1'(k_z)/P_1(k_1)$ (line 1) does not contradict experimental spectra obtained during *in situ* rocket measurements in the high latitude ionosphere [1]. Estimates of changes in the slope of the irregularity spectra (changes in the spectral index, $1 < p < 8$, if a power-law dependence, k^{-p}, is taken for description of the spectrum) as well as an estimate of the rms level of plasma fluctuations made with the use of (2), ≈ 1.2 % ($k_1 = 10^{-3}$ m^{-1}, $k_2 < k_d \approx 0.2$ m^{-1}) are consistent with experimental data gathered during the ROSE campaign [5, 7].

CONCLUSION

Thus, it was shown that the spectra of the plasma irregularities that can be caused by neutral turbulence in the lower ionosphere have to be quite close to an isotropic one, although some their deviations from isotropy may exist on the edges of the considered wave-number range. These deviations result from changes in a relative role of the geomagnetic field (more important for larger wave numbers) and of the gradient of mean plasma density (more important for smaller wave numbers) in creating the plasma irregularities of different scales. Estimations of slope of the irregularity spectra and of the rms level of plasma density fluctuations made here do not contradict the data gathered during the rocket-radar simultaneous experiment in the lower ionosphere at high latitudes [1, 5, 7]. It seems useful for testing the present results to conduct an experiment that measures simultaneously the irregularity spectrum in two directions with the use of rocket and radar instruments (see, e.g., [1, 4, 6, 7]), and the pertinent parameters of both the lower ionosphere and the neutral atmosphere turbulence.

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