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ELECTRODYNAMICS AND WAVE PROPAGATION

The Inhomogeneous Structure of the Daytime Venusian Ionosphere Studied by Venera 15 and Venera 16 via Radio Sounding

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Abstract—The inhomogeneous structure of the Venusian daytime ionosphere is investigated on the basis of the data provided by the Venera 15 and Venera 16 space probes. The experimental data obtained from two-frequency radio sounding are restored, processed, and saved on modern media. Frequency and signal-power variations are analyzed, and, as a result, ionized layers on the solar illuminated planet's daytime side are discovered at altitudes of 80–110 km. Results of spectral processing of frequency fluctuations observed during sounding of the upper region of the Venusian daytime ionosphere are presented. In this region, the electron concentration monotonically decreases with altitude up to the ionopause. Electron-concentration irregularities with dimensions of 5–60 km are revealed. The intensity and spectral index of the spatial spectrum of the ionospheric turbulence are estimated. Reliable information on the turbulence of the planet's ionized shell is obtained for the first time.

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INTRODUCTION

The ionosphere on Venus' daytime and night-time sides was discovered by means of radio sounding during the flight of the Mariner 5 orbiter in 1967 [1–3]. A similar experiment was carried out during the flight of Mariner 10 in 1974 [4, 5]. Multiple radio sounding of the Venusian ionosphere was realized for the first time in 1975 with the help of Venera 9 and Venera 10 [6–8]. On the basis of the obtained results, the most important features of the behavior of the daytime ionosphere have been revealed and its altitude profiles of electron concentration $N(h)$ have been determined in the interval of the Sun's zenith angles $Z_{\odot} = 10°–87°$ for the period of minimum solar activity. Later, similar experiments were performed with the help of the Pioneer Venus Orbiter (PVO) (1978–1982) [9–11] and Venera 15 and Venera 16 (1983, 1984) [12, 13] during the period of maximum solar activity and during the period of the solar activity's decrease. Thus, after several long series of radio occultation experiments, a great bulk of data on regular altitude distributions of the plasma concentration in the Venusian ionosphere have been accumulated for various conditions of solar illumination and phases of the cycle of solar activity. Now, the Venusian ionosphere is being explored with the use of the Venus Express space vehicle (SV) [14].

In this study, we hope to extend the capabilities of the radio-sounding method applied for investigations of the irregular structure and turbulence of the ionosphere. For this purpose, records of primary information obtained from sessions of double-frequency radio sounding of the Venusian daytime ionosphere have been restored and saved on modern media. The sounding was performed by means of coherent signals produced by Venera 15 and Venera 16. The sounding data have provided 73 altitude profiles for the Sun's zenith angles ranging from 52° to 90°. A new technique and software have been developed for the study of the fine ionospheric structure and random irregularities of the electron concentration. As a result, the frequencies and power of coherent decimeter- and centimeter-wavelength signals have been measured at the highest possible time resolution.

1. EXPERIMENTAL CONDITIONS AND TECHNIQUES OF MEASUREMENTS AND PROCESSING OF OBSERVATION RESULTS

The Venusian ionosphere was explored with the help of Venera 15 and Venera 16, which carried a transmitting system that simultaneously radiated two coherent decimeter- and centimeter-wavelength signals. Double-frequency radio sounding was performed from October 12, 1983, to September 24, 1984. When the stations went behind and emerged from behind the planet, the onboard radio system radiated two coherent signals toward the Earth. The signals had wavelengths of λ_1 = 32 cm and λ_2 = 8 cm and the frequency ratio $p = f_2/f_1 = 4$. The ground-based equipment detected the signals and performed narrowband filtering by tracking filters. The signals were encoded with the help of a double-channel eight-digit analog-to-digital converter; therefore, there were no relative time shifts of the two coherent signals. Processing involved measurements of the signals' powers and reduced frequency difference δf, expressed by the formula

$$\delta f = \frac{p}{(p^2 - 1)}(pf_1 - f_2), \quad (1)$$

where f_1 and f_2 are the frequencies of received decimeter-and centimeter-wavelength signals. The plasma effect observed on the SV–ground-based-station path led to a change in the frequencies of a decimeter-wavelength signal, and quantity δf can be assumed to have been equal to this change.

In the experiments on radio sounding of the Venusian daytime ionosphere, the ionospheric and tropospheric components overlapped in time. Only the presence of two coherent signals made it possible to eliminate the effect of the neutral component through analysis of reduced frequency difference δf for determination of the characteristics of the lower ionosphere.

In order to associate the observation results with the planet's surface, we employed ballistic data on minimum distance h_0 between the Venusian surface and the station–Earth sight line and data on the rate $V = dh_0/dt$ of the time variation of this distance.

The newly developed technique provides for highly accurate estimation of the parameters of radio signals. In order to detect a signal within the entire frequency band (~275 Hz), we employed a digital-filter bank with fixed frequencies that was implemented with the use of the discrete Fourier transform. A reference complex oscillation can be formed and digital heterodyning can be performed on the basis of preliminary estimates of the parameters of the detected signal. The digital heterodyning provides for compensation of frequency variations in the analyzed signal. Elimination of regular variations of the signal frequency and smearing of the spectral line increases the signal-to-noise ratio (SNR) for the mixture of the received harmonic signal and additive noise.

In order to determine the radio-signal parameters, we analyzed the quadrature components of the complex oscillation $y(t) = y'(t) + jy''(t)$ at the output of a matched filter. The signal power was determined from the relationship

$$P = y'(t)^2 + y''(t)^2.$$

Phase $\Phi(t)$ of output complex oscillation $y(t)$ was calculated from the formula

$$\Phi(t) = \arctan(y''(t)/y'(t)).$$

within the interval $-\pi < \Phi(t) < \pi$. The estimated difference $\Phi(t + \Delta t) - \Phi(t)$ of phases on neighboring time intervals is the estimated increment of the signal phase over time interval Δt. Hence, it is possible to estimate the deviation of the signal frequency from the center frequency of the matched filter,

$$f_0 = (\Phi(t + \Delta t) - \Phi(t))/(2\pi\Delta t)$$

and to form a more accurate reference oscillation. The successive-approximation method yields the minimum possible value of f_0; thus, the maximum SNR is reached at the output of the matched filter. Therefore, the optimal estimates of the radio-signal power and frequency can be obtained with an accuracy corresponding to the theoretical constraints due to the noise effect.

In the case of this technique, estimated signal power P is not distorted by the shape of the frequency response of the filter and by smearing of the signal's spectral line. The estimated signal frequency is dependent on the frequency of the reference oscillation that is employed for heterodyning. The technique was tested through computer simulation of a signal. The test has shown that the error of the determined frequency of a harmonic signal does not exceed $\sim 1 \times 10^{-3}$ Hz upon averaging over 1 s and the error of the determined power does not exceed ~2% if the SNR ranges from 10^4 to 4×10^2 within a band of 1 Hz. The latter condition corresponds to the conditions of radio sounding by Venera 15 and Venera 16.

2. ANALYSIS OF THE MEASURED SIGNAL FREQUENCY AND POWER

A signal's frequency and power variations Δf and W, respectively, that are due to the effect of the sounded ionosphere are coupled with the altitude profile of electron concentration $N(h)$ and radio-wave refraction angle ξ through the relationships [15]

$$\Delta f = \frac{e^2 V}{2\pi mfc}\frac{dN_i}{d\rho}, \quad (2)$$

$$N_i(\rho) = 2\int_{\rho}^{a+h_i} \frac{rN(r)dr}{\sqrt{r^2 - \rho^2}}, \quad (3)$$

$$W = \left(1 - L\frac{d\xi}{d\rho}\right)^{-1}, \quad (4)$$

$$\Delta f = -fV\xi/c, \quad (5)$$

$$\rho = a + h_0 + L\xi, \quad (6)$$

where e and m are the electron charge and mass, respectively; c is the velocity of light in free space; f is the frequency of a radio signal; N_i is the integral electron concentration on the radio-wave path in the ionosphere; ρ is the target parameter of the radio ray; a is the planet's radius; h_i s the upper boundary of the ionosphere (the ionopause altitude); $r = a + h$; and L is the distance between an SV and the planet's disk.

Relationships (2)–(6) provide for solution of the direct problem of ionospheric sounding, i.e., for deter-

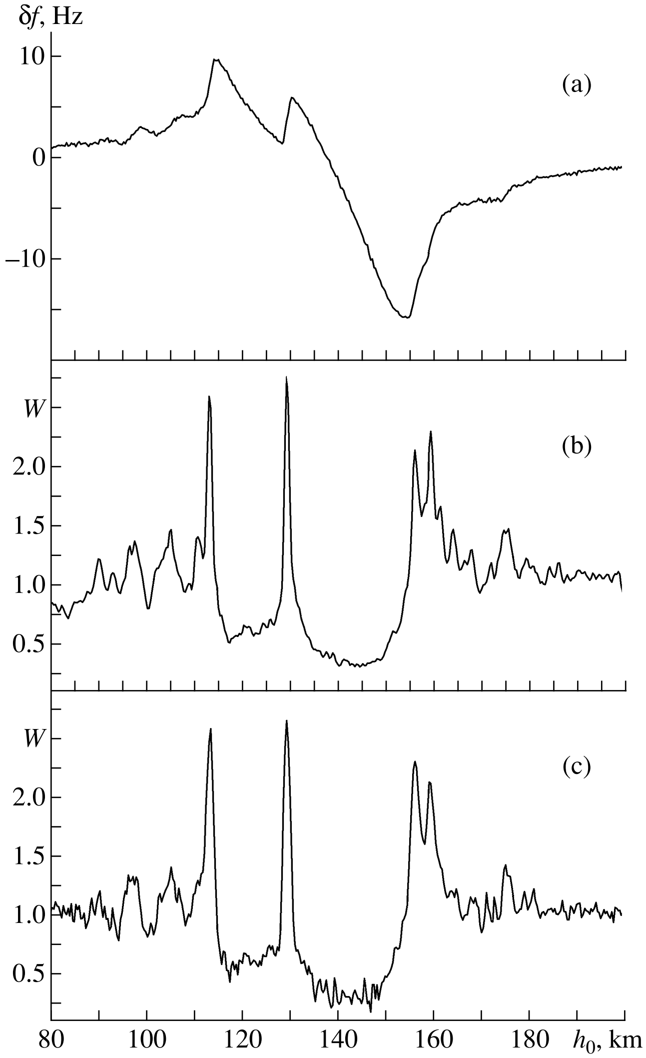

Fig. 1. (a) Reduced frequency δf and (b) power W of a decimeter-wavelength signal as functions of altitude h_0 (for the radio exit of October 14, 1983) and (c) the change of the power determined from frequency measurements.

mination of variations $\Delta f(h_0)$ and $W(h_0)$ from known altitude distribution $N(h)$ of the electron concentration. Taking into account that

$$L\frac{d\xi}{d\rho} = 1 - \frac{V}{d\rho/dt},$$

$$\frac{d\rho}{dt} = V + \frac{d\xi}{dt}L$$

and using (5), we obtain

$$W = 1 + \frac{cL}{fV^2}\frac{d}{dt}\Delta f(t). \quad (7)$$

whence it follows that the refraction-induced variation of the signal power in the sounded ionosphere is proportional to the time derivative of frequency shift Δf.

Figure 1 shows results of radio sounding of the region of the main and lower ionization maxima of the Venusian daytime ionosphere. The solar zenith angle is $z_\odot \approx 58.7°$. The results were obtained during the radio-exit session on October 14, 1983. The measured reduced frequency h_0 (Fig. 1a), normalized power W of a decimeter-wavelength signal (Fig. 1b), and power W calculated from frequency data according to formula (7) (Fig. 1c) are presented as functions of altitude h_0. Dependences $W(h_0)$ obtained by means of different methods practically coincide (Figs. 1b, 1c). This circumstance means that relationship (6) makes it possible to find refraction-induced power variation W of a signal only via frequency measurements.

Figures 2a, 2b, 3a, and 3b show dependences $\delta f(h_0)$ and $W(h_0)$ measured within the same altitude interval in two other radio-exit sessions. Dependences $\delta f(h_0)$ depicted in Figs. 1a, 2a, and 3a have two characteristic maxima and two characteristic minima at altitudes of 115–155 km. These extrema are due to the effect of the main and lower ionization maxima. A specific feature of the power behavior (Figs. 1b, 2b, 3b) is the presence of distinct maxima related to the effect of radio-wave refraction in the sounded ionosphere. During sounding of the Venusian daytime ionosphere, the power of a decimeter-wavelength signal increases several times.

The following specific features of data obtained from radio sounding over the altitude interval $h_0 \approx 160$–170 km have been revealed:

(i) the presence of inflections on dependences $\delta f(h_0)$ (Figs. 1a, 2a, 3a),

(ii) the presence of two additional maxima on curve $W(h_0)$, and

(iii) the presence of a protrusion on the $N(h)$ profiles at heights of 160–165 km [16].

The presence of a protrusion that is often observed on the dependences obtained from the data provided by the Venera 15 and Venera 16 stations indicates that, at the aforementioned altitudes, the electron temperature abruptly increases. Note that this temperature governs the rate of dissociative recombination of O_2^+ ions.

Currently, the Venusian ionospheric region situated under the lower ionization maximum at altitudes of 80–110 km is the least studied. This circumstance is due to the fact that the reliable altitude distribution of the electron concentration cannot be found from radio-sounding data, because of large errors in the solution of the inverse problem. According to theoretical models based on known photochemical processes, the electron concentration in the Venusian lower daytime ionosphere rapidly and regularly decreases with the altitude [16]. However, the primary radio-sounding data (see Figs. 1–3) indicate the existence of stratified objects in the lower ionosphere that are especially distinctly seen on depen-

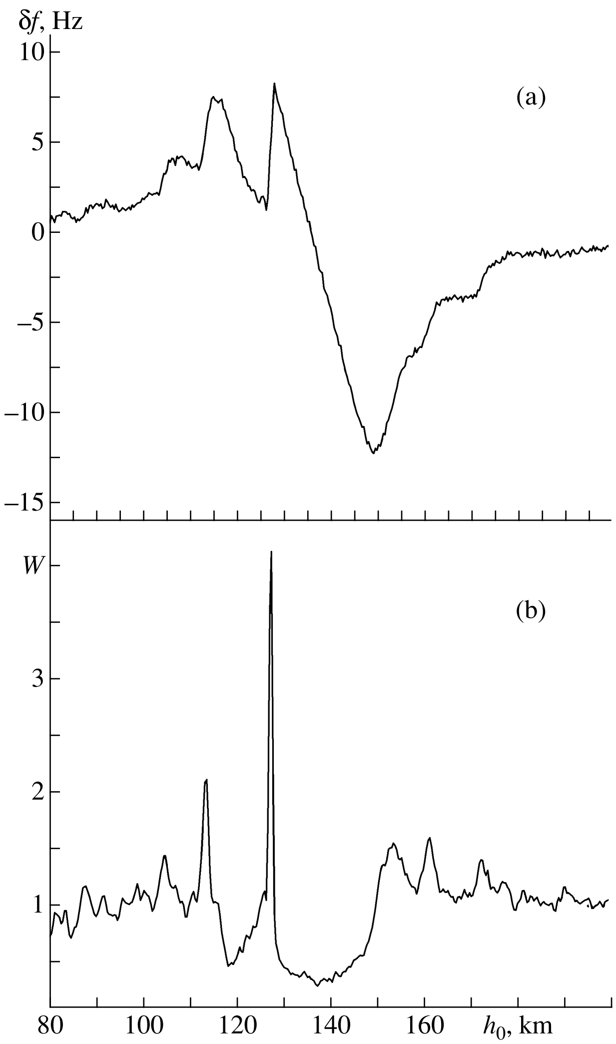

Fig. 2. (a) Reduced frequency δf and (b) power W of a decimeter-wavelength signal as functions of altitude h_0. The results are obtained from the data of the radio exit of October 22, 1983. ($z_\odot \approx 68.8°$).

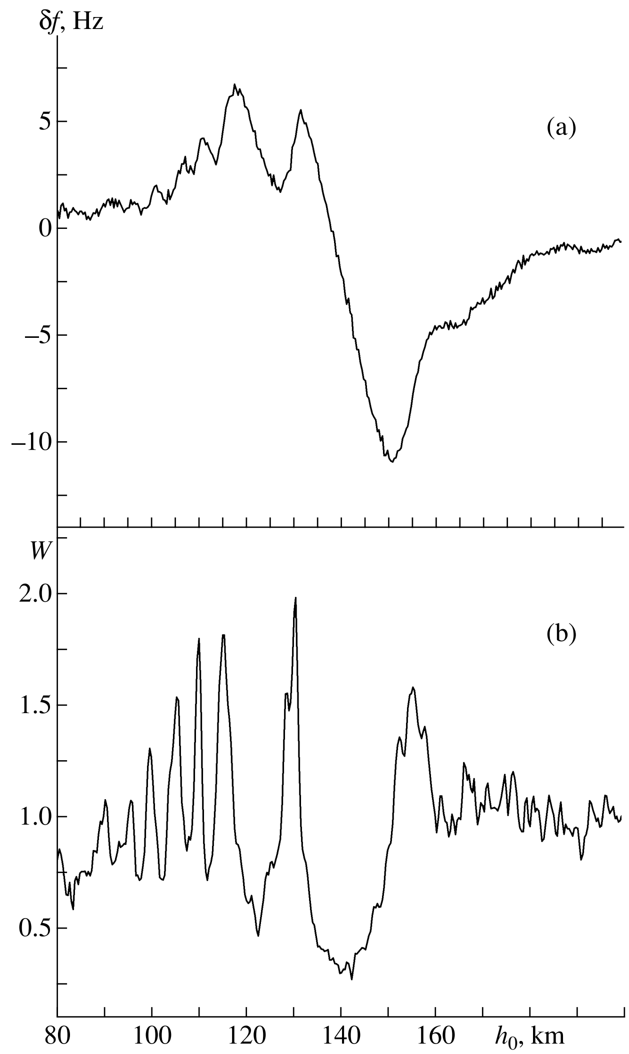

Fig. 3. (a) Reduced frequency δf and (b) power W of a decimeter-wavelength signal as functions of altitude h_0. The results are obtained from the data of the radio exit of October 25, 1983. ($z_\odot \approx 73.5°$).

dences $W(h_0)$. The most extraordinary situation is observed for the data of the session of October 25, 1983, (Fig. 3b), where the dependence of the signal power on altitude h_0 exhibits several pronounced maxima and minima.

3. SPECTRAL PROCESSING OF FREQUENCY DATA

Strong fluctuations of the signal frequency were registered when the PVO entered the Venusian daytime ionosphere [17]. The path covered by an S-band signal (with the wavelength λ = 13 cm and frequency f = 2295 MHz) passed through the region of the upper ionosphere near the subsolar point. The comparison of observed radio effects with plasma and magnetic PVO onboard measurements has shown that fluctuations of the radio-wave frequency are due to the irregularities of plasma concentration N that appear when the dynamic pressure of the solar wind exceeds the ionosphereic pressure. Plasma perturbations are accompanied by large-scale magnetic fields induced by the solar wind in the regions below the ionopause. The analysis of frequency data shows that the rms value of fluctuations of N is $\sigma_N \approx 3 \times 10^4$ cm^{-3}.

Moreover, in radio-occultation experiments performed with the use of the PVO, frequency fluctuations of an S-band sounding signal were observed during sounding of the daytime ionosphere [17]. The results obtained with the help of the PVO indicate that the radio-occultation method can be applied not only to determination of regular altitude profiles of the electron concentration but also to exploration of the inhomoge-

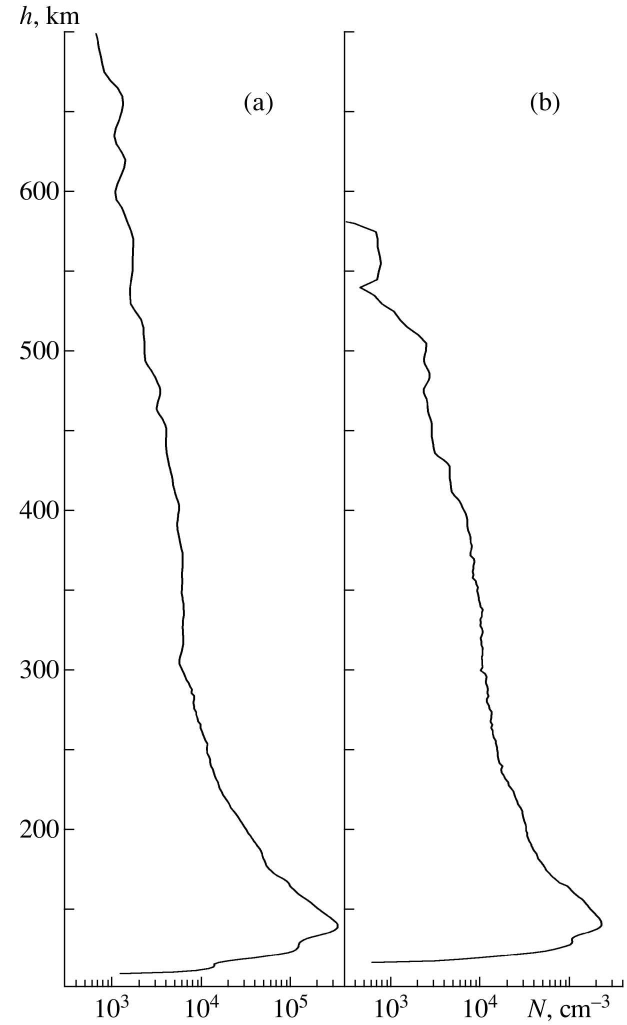

Fig. 4. Altitude distributions $N(h)$ of the electron concentration in the Venusian daytime ionosphere: (a) the radio exit of October 22, 1983, $z_{\odot} = 69°$ and (b) the radio entry of October 14, 1983, $z_{\odot} = 82°$.

neous structure of planets' ionospheres and of their interaction with the solar wind.

Investigations started in [17] can be continued with the use of measurements of reduced frequency difference $\delta f(t)$. These data were obtained during radio sounding of the Venusian daytime ionosphere with the signals from Venera 15 and Venera 16. However, in contrast to the authors of study [17], we investigate random irregularities—the plasma turbulence—with the use of the spectral technique applied for similar purposes in studies of the turbulence of circumsolar plasma. These studies employ results of radio sounding of this plasma with signals of SVs traveling behind the Sun [15, 18].

In order to more effectively realize the capabilities of the technique for determination of spectrum $G_f(\nu)$ of frequency fluctuations in the high-frequency range, it is necessary to measure the frequency with a sufficiently small time step Δt. We choose the value $\Delta t = 0.116$ s, which corresponds to the Nyquist frequency $\nu_N \approx 3.5$ Hz. Spectra $G_f(\nu)$ are calculated from the results of radio sounding of the upper daytime ionosphere for target radio-ray distances h_0 exceeding 250 km. In this region, the signal frequency gradually changes with altitude. Therefore, the trend due to regular altitude variations of the electron concentration can be reliably eliminated from measurement results. The length of the altitude interval within which the spectrum is calculated is $\Delta h = MV\Delta t$, where M is the number of successive temporal sample values of the signal frequency. Quantity Δh reaches 120 km for $M = 256$ and $V = 3.6$ km/s (radio entry) and 180 km for $V = 6$ k (radio exit). Therefore, spectral processing should be performed for data of radio sounding of an extended ionosphere whose ionopause has an altitude of several hundred kilometers. Figure 4 shows two altitude profiles of the electron concentration that are obtained from the data of the radio exit of October 22, 1983 (Fig. 4a), and radio entry of October 14, 1983 (Fig. 4b). Both of the distributions characterize the ionosphere observed at large solar zenith angles (69° and 82°, respectively) and the ionopause altitudes 700 and 600 km.

The fast Fourier transform (FFT) is applied for spectral processing of three radio sounding sessions. The results obtained with the use of the FFT-256 algorithm are presented in Figs. 5 and 6 on the double logarithmic scale. Spectra $G_f(\nu)$ calculated from the data of the radio entry of October 10, 1983, are depicted in Figs. 5a–5c for the following three altitude intervals: 250–357, 400–501, and 700–787 km. The last of the spectra from Fig. 5c is obtained from the measurements on a reference region free from the effect of ionospheric plasma for target distances h_0 exceeding the ionopause altitude $h_i \approx 600$ km. In this case, spectra $G_f(\nu)$ are practically independent of fluctuation frequency ν and determined by instrumental noise. It is seen from Figs. 5a and 5b that, when $h_0 < h_i$, the spectrum can be regarded as a noise spectrum only if $\nu \geq 1$ Hz, while, as ν grows, spectral density $G_f(\nu)$ naturally decreases in a fluctuation-frequency interval of 0.1–0.7 Hz and can be approximated by the power function $\nu^{-\alpha_f}$. As is known [15, 18], spectral index α_f of the fluctuation-frequency spectrum is less than the exponent of the spatial spectrum of the plasma turbulence by three. Quantity α_f is 0.64 for the spectrum from Fig. 5a and 0.6 for the spectrum from Fig. 5b. This quantity is close to the value $\alpha_f = 0.67$, which characterizes the Kolmogorov–Oboukhov turbulence.

Note that the found value of spectral index α_f can be regarded as an approximate estimate, because the intensity of frequency fluctuations that are due to random ionospheric irregularities is substantially lower than the

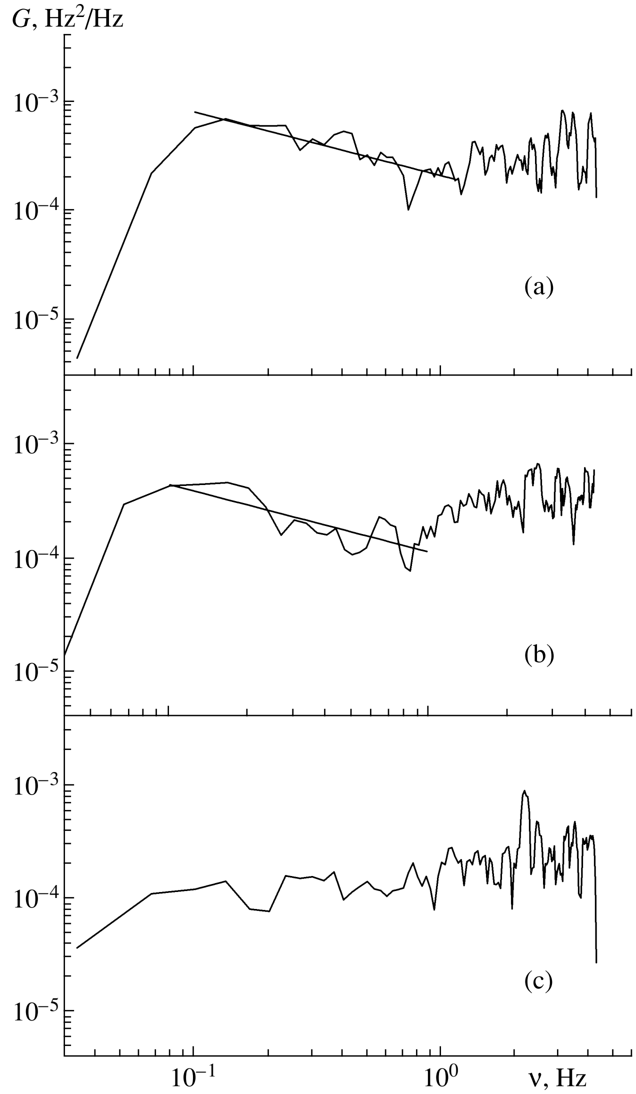

Fig. 5. Spectra $G_f(\nu)$ of frequency fluctuations for three altitude intervals: (a) 250–357 km, (b) 400–501 km, and (c) 700–782 km. The results are obtained for the radio entry of October 14, 1983, and $z_\odot = 82°$. The straight lines show the power dependence.

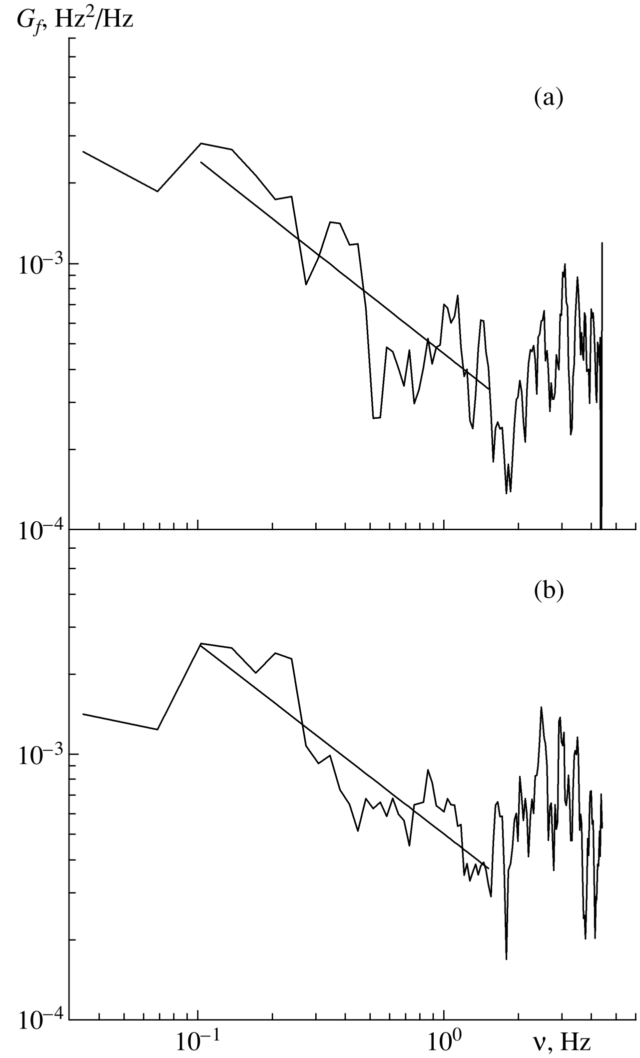

Fig. 6. Spectra $G_f(\nu)$ of frequency fluctuations: (a) the radio exit of October 22, 1983, $z_\odot = 69°$, and the altitudes 250–430 km and (b) the radio exit of October 25, 1983, $z_\odot = 73.5°$, and the altitudes 300–480 km. The straight lines show the power dependence.

component introduced by noise. Thus, the total power of fluctuations for the spectrum from Fig. 5a is $\sigma^2 \approx 1.57 \times 10^{-3}$ Hz^2 and the intensity of fluctuations in the frequency interval $0.1 < \nu < 0.7$ Hz, where the turbulence effect is observed, is 3.2×10^{-4} Hz^2. We can subtract the noise spectrum (Fig. 5c) from the spectra depicted in Figs. 5a and 5b and, thus, obtain another estimate of α_f, which, to a certain extent, takes into account noise. The spectral index found from the difference spectrum in the same fluctuation-frequency interval $0.1 < \nu < 0.7$ Hz turns out to be larger than ($\alpha_f \approx 0.75$), but also close to, the value $\alpha_f \approx 0.67$.

Let us consider frequency fluctuations due to the ionosphere and, on the basis of the obtained spectra, estimate the power of these fluctuations as $\sigma_f^2 = \sigma^2 - \sigma_n^2$, where σ_n^2 is the intensity of the noise component. The quantity σ_n^2 can be found from the noise spectrum (Fig. 5c) that is determined from observations in the region free from the ionosphere effect. The rms value of frequency fluctuations turns out to be $\sigma_f = 0.013$ and 0.008 Hz for the spectra from Figs. 5c and 5b, respectively.

Two more spectra of frequency fluctuations are calculated from the data of two radio sounding sessions and displayed in Fig. 6. The same technique is applied to find (on the longer interval $0.1 < \nu < 1.0$ Hz) indexes α_f and standard deviations σ_f from these spectra. Quantities σ_f and α_f are approximately equal to the respective values for both sessions within the measurement error: $\sigma_f \approx 0.023$ Hz and $\alpha_f \approx 0.72$. Since the turbulence-induced power of frequency fluctuations is proportional to velocity V, quantity σ_f is greater for radio exits (V = 6.2 km/s) than for the radio entry (V = 3.6 km/s). The characteristic dimension ($l = V/\nu$) of electron-concentration irregularities that determines spectrum $G_f(\nu)$ in the frequency interval 0.1–1 Hz ranges from 6 to 60 km.

There are theoretical relationships that allow determination of the turbulence characteristics of the solar-wind plasma from frequency fluctuations of radio waves radiated by SVs traveling behind the Sun. These relationships can be applied to find variance σ_N^2 of electron-concentration fluctuations in the ionosphere from radio sounding data.

By analogy with the solar wind, we characterize the turbulence of ionospheric plasma with the spectrum of irregularities of the electron concentration. For the isotropic case, this spectrum has the following form [18]:

$$\Phi_N(q) = C^2 \frac{\exp(-q^2/q_m^2)}{(q_0^2 + q^2)^{p_N/2}}, \tag{8}$$

where q_m and q_0 are the spatial wave numbers corresponding to the internal ($l_m = 2\pi/q_m$) and external ($L_0 = 2\pi/q_0$) turbulence scales, respectively; p_N is the spectral index of the turbulence spatial spectrum; and C^2 is the normalizing factor that characterizes fluctuation intensity σ_N^2 [18] and is expressed as

$$C^2 = \sigma_N^2 \frac{\alpha_f}{(2\pi)^{3/2}} \frac{\Gamma(p_N/2)}{\Gamma[(p_N - 1)/2]} q_0^{\alpha_f}. \tag{9}$$

Assume that $p_N > 3$. Then, $\alpha_f > 0$.

If the geometric-optics approximation is valid and the hypothesis of frozen turbulence holds, the temporal energy spectrum of frequency fluctuations of radio waves transmitted through a turbulent plasma layer of thickness L is represented as [19]

$$G_f(\nu) = \frac{1}{\pi} r_e^2 \lambda^2 \sigma_N^2 L \alpha_f V \nu_0^{\alpha_f} \nu^2 \times \exp\left(-\frac{\nu^2}{\nu_m^2}\right) (\nu_0^2 + \nu^2)^{(-2-\alpha_f)/2}, \tag{10}$$

where $r_e = 2.82 \times 10^{-13}$ cm is the classic electron radius.

The use of (10) and integration over fluctuation frequencies ν yield variance σ_f^2 of frequency fluctuations. If the Nyquist frequency is much lower than the frequency corresponding to internal turbulence scale ν_m, we can find an approximate expression for σ_f^2 in the interval of fluctuation frequencies from ν_1 to ν_2 [18]:

$$\sigma_f^2 = \frac{r_e^2 \lambda^2 \sigma_N^2 L \alpha_f V \nu_0^{\alpha_f}}{\pi(1 - \alpha_f)} (\nu_2^{1-\alpha_f} - \nu_1^{1-\alpha_f}). \tag{11}$$

The rms values of electron-concentration fluctuations in the Venusian daytime ionosphere can be found from values σ_f according to (4). Assume that external scale L_0 equals the altitude dimension of the ionosphere $h_i \approx 500$ km, the effective thickness of the layer is $L = 2 \times 10^3$ km, $\alpha_f = 0.67$ (the Kolmogorov–Oboukhov turbulence), $\nu_1 = 0.1$ Hz, $\nu_2 = 1.0$ Hz, $V = 6.2$ km/s, and $\sigma_f = 2.3 \times 10^{-2}$ Hz. Under these conditions, $\sigma_N \approx 10^3$ cm^{-3}. As follows from Fig. 4a, this value is less than the average electron concentration in the Venusian daytime ionosphere at the altitudes 250–400 km by a factor of approximately 10–15.

CONCLUSIONS

Additional processing performed with a high time resolution of data obtained in several sessions of double-frequency radio sounding of the Venusian daytime ionosphere has yielded the following results.

It has been shown from theoretical relationships and experimental data that the power change due to radio-wave refraction in the sounded ionosphere is determined by the rate of variation of the signal frequency in time. The behavior of the signal frequency and power as functions of the radio-ray altitude indicates the existence of irregular ionization layers below the lower maximum of the ionization of the Venusian daytime ionosphere in the altitude interval 80–110 km.

Spectral processing of radio-signal frequency fluctuations measured during sounding of the Venusian ionosphere has been performed for the first time. The obtained spectra show the presence of random irregularities of the electron concentration in the Venusian upper daytime ionosphere. The rms value of these irregularities is about ~10^3 cm^{-3}. The exponent of the 3D spatial spectrum of the plasma turbulence is close to the analogous characteristic of the Kolmogorov–Oboukhov spectrum.

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