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Activity of Small-Scale Internal Waves in the Northern Polar Atmosphere of Venus by Radio Occultation Measurements of Signal Intensity (Λ = 32 cm) from *Venera-15* and *-16* Satellites

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Abstract—The radio occultation measurements of the signal intensity (λ = 32 cm) of the *Venera-15* and *-16* satellites, carried out from October 16 to October 31, 1983, are used to analyze the activity of internal waves in the northern polar atmosphere of Venus. Observations of the intensity of radio waves provide important information about the fine-scale structure of the planet's atmosphere. Comparison of radio occultation measurements and the results of the standard wave theory shows that small-scale fluctuations of the received signal intensity are caused by the spectrum of vertically propagating internal gravity waves. The vertical length of these fluctuations at altitudes of more than 61.5 km is about ~1 km. The model developed for the radiative damping of intensity fluctuations with altitude in the atmosphere of Venus assumes that the intrinsic frequencies of the identified internal waves (measured in a frame of reference moving together with the undisturbed flow) in the sessions under study vary from 3.5×10^{-4} to 9.5×10^{-4} rad/s, and the ratio of horizontal and vertical wavelengths is in the range from 57 to 21.

Keywords: radio occultation measurements, signal intensity fluctuations, Venus' atmosphere, radiative damping, internal gravity waves

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INTRODUCTION

Wave processes have a significant impact on the circulation, chemical composition, thermal regime and variability of planetary atmospheres. An important role of internal gravity waves (IGWs) is associated with their providing an effective way of transferring energy and momentum from the lower atmospheric levels to the upper. Sources of internal waves in the atmosphere can be thermal contrasts near the surface, topography, shear and convective wind instabilities, frontal processes, etc. In the absence of energy dissipation, the amplitude of wave disturbances of wind speed or temperature grows approximately exponentially with an increase in altitude in the Earth's atmosphere; therefore, disturbances with a small amplitude near the surface can produce significant effects at high altitudes where the waves break and the energy and momentum are transferred to the unperturbed flow. Since IGWs are a characteristic feature of a stably stratified atmosphere, similar effects can be expected in the atmospheres of Venus and Mars. Interpretation of observations of fluctuations in wind speed, temperature, or density in the planet's atmosphere is often based on a model of a wide spectrum of waves that generate these fluctuations. The spectral description implies that the wave field of fluctuations consists of many components with different scales. In many cases, the experimental spectra of temperature, density, or wind speed fluctuations in the atmosphere demonstrate discrete (single) narrow peaks against the background of a smooth spectrum, which indicate a quasiperiodic structure of disturbances in a certain range of altitudes. The results of direct probe measurements in the Earth's stratosphere indicate that the formation of such a structure may be due to the propagation of a monochromatic wave, which is in a state of saturation due to shear instability in the atmosphere.

The advantage of radio occultation measurements is a wide geographical and temporal coverage of the studied regions, which allows for global monitoring of the state of the atmosphere (Gubenko et al., 2016a, 2016b, 2018a). In the period from October 1983 to September 1984, using the *Venera-15* and *-16* satellites, we performed intensive radio occultation studies of the atmosphere of Venus. The orbits of these satellites were such that they went behind the planet in the northern hemisphere, and came out from behind it in the southern hemisphere. Two-frequency radio observations (wavelengths 5 and 32 cm) were carried out in 176 atmospheric regions located on the day and night sides of the northern and southern hemispheres of the planet. In the circumpolar and polar regions of the southern hemisphere of Venus, where previously only single measurements were carried out, new data on atmospheric characteristics were obtained for 20 regions. The results found on the basis of these measurements include: (I) vertical profiles of density, pressure, temperature, as well as characteristic parameters for 42 regions of the polar and circumpolar atmosphere at altitudes of 42–90 km and estimates of errors in the determined quantities (Yakovlev et al., 1991); (II) characteristics of thin regular layers in the atmosphere of Venus (Gubenko and Andreev, 2003; Gubenko et al., 2008a); (III) vertical profiles of sulfuric acid vapor content and absorption of 5-cm radio waves in the planet's atmosphere (Gubenko et al., 2001); (IV) altitude and latitude dependences of the zonal wind speed in the atmosphere of Venus (Gubenko et al., 1992; Vaganov et al., 1992; Gubenko and Kirillovich, 2018a); (V) vertical profiles of temperature, pressure, and temperature gradients for the middle latitudes of the planet at altitudes of 40–90 km (Matyugov et al., 1994).

We use some of our earlier results and measurements of the intensity of radio occultation signals (wavelength λ = 32 cm) from the satellites *Venera-15* and *-16* to study small-scale internal waves in the northern polar atmosphere of Venus at altitudes above 61.5 km. The aim of the work is to analyze the measurements of the intensity of radio waves, carried out in the period from October 16 to October 31, 1983, to study internal waves in the polar atmosphere of the planet, which is based on the model of radiative damping of intensity fluctuations with increasing altitude. The altitude is measured from the level of the surface of Venus with a radius of 6051 km.

RADIATIVE DAMPING OF INTERNAL ATMOSPHERIC WAVES: ANALYSIS OF RADIO OCCLUSION MEASUREMENTS OF SIGNAL INTENSITY FROM *VENERA-15* AND *-16* SATELLITES

Observations of the intensity of radio occultation signals provide important information about the small-scale structure of the planet's atmosphere. In many respects, our method for determining the characteristics of atmospheric waves is similar to the method proposed earlier by Hinson, Jenkins (1995) and Tellmann et al. (2012). The authors of these works assumed that the radiative damping of wave disturbances with altitude in radio occultation experiments is the main process contributing to the dissipation of IGW energy with a vertical wavelength of <4 km. Figure 1 shows examples of measurements of the normalized intensity (I) of a signal with λ = 32 cm for three analyzed radio occultation sessions of *Venera-15* and *-16*. The I value is defined as the ratio of the signal intensity values measured at the given moment and in free space before entering the planet's atmosphere. The normalized intensity I is a dimensionless quantity, and it remains approximately constant (~ 1.0) until the transillumination of the neutral atmosphere begins (relative time ~0 s, altitude ~100 km). Figure 1 clearly shows the response of radio waves when passing the daytime ionosphere near the terminator (the zenith angle of the Sun is $Z_\odot$ = 85.8° for session 24 and $Z_\odot$ = 87.2° for session 30) and the night ionosphere near the terminator ($Z_\odot$ = 95.4° for session 42). Since the minima of the intensity of the radio occultation signal correspond to the local maxima of the electron density (Gubenko et al., 2018b; Gubenko and Kirillovich, 2019), from the data presented in Fig. 1, it follows that the structure of the ionosphere of Venus near the terminator on the day side is two-layer, and on the night side it is single-layer. Taking into account that the vertical speed of descent of the radio ray here is ~4.3 km/s (Gubenko et al., 2008a), it can be found that the ionospheric maxima near the terminator on the day and night sides of the planet are located at altitudes of ~150 km.

The parameters of the radio occultation sessions of *Venera-15* and *-16*, which we analyzed to monitor the activity of internal waves and determine their characteristics in the northern polar atmosphere of Venus, are presented in Table 1. Here are indicated the number and time of the measurement session, the spacecraft, the latitude and longitude of the sounded region, the zenith angle of the Sun ($Z_\odot$), the tropopause altitude (h_t) and the altitude of the temperature minimum ($h_{\min}$) for the measurement area. These characteristics were found during data processing to reconstruct atmospheric density, pressure, and temperature profiles (Yakovlev et al., 1991).

The radio occultation measurements analyzed in this work were carried out during the almost vertical ingresses of the *Venera-15* and *-16* satellites behind the planet (Yakovlev et al., 1991; Gubenko et al., 2008a). The geometry of the radio transillumination experiment was such that the perigee point of the ray path barely shifted horizontally during the measurement session (~2 min). The radial velocity V_n of these satellites, perpendicular to the trajectory of the radio ray, was V_n = 4.3 km/s. The vertical speed of descent of the radio ray in the atmosphere V_r is determined by the value of the speed V_n and the value of the average refractive attenuation of the signal $\langle X \rangle$ using the relation $V_r = V_n\langle X \rangle$ (Gubenko et al., 2008a). The vertical velocity of the radio ray when it enters the atmosphere (altitude ~100 km, $\langle X \rangle \approx 1.0$) was ~4.3 km/s. When the ray passed through lower atmospheric levels (~62 km, $\langle X \rangle \approx 0.1$) located near the tropopause, its value was ~0.43 km/s. The indicated values of the ray descending velocity are many times higher than the average velocities of the probed structures in the atmosphere. Usually, the duration of a radio occultation session is about 2 minutes, so the satellite radio hologram con-

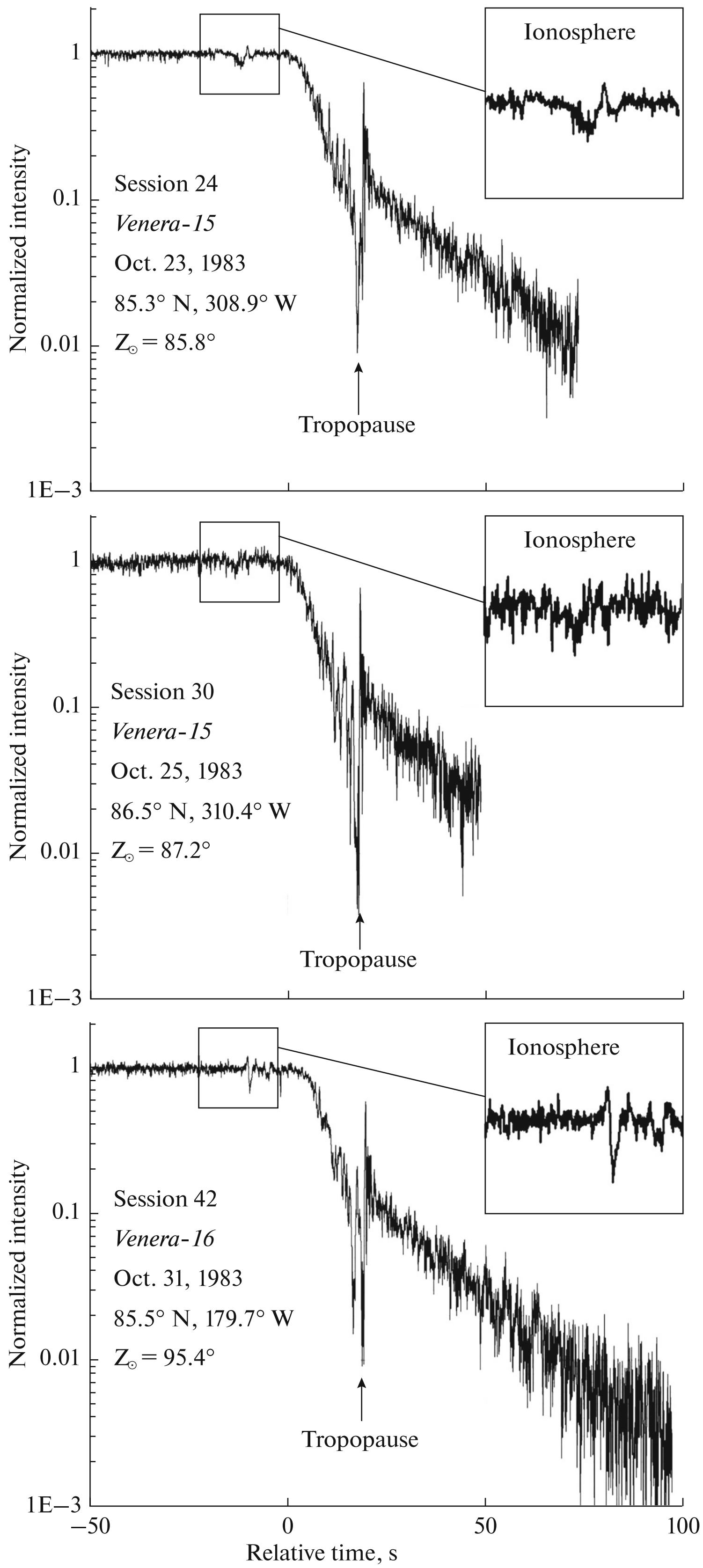

Fig. 1. Dependences of the signal intensity at $\lambda = 32$ cm on time in the northern polar atmosphere of Venus for radio occultation sessions 24, 30 and 42 (ingresses) of the *Venera-15* and *-16* satellites. The relative time $t = 0$ s corresponds to a ray perigee altitude of ~100 km above the planet's surface with a radius of 6051 km. The tropopause of the probed regions of the atmosphere are located at altitudes of ~57.6 km (sessions 24, 30) and ~59.0 km (session 42) (Yakovlev et al., 1991).

Table 1. Parameters of radio occultation sessions, in which the characteristics of internal waves in the northern polar atmosphere of Venus were determined

Session 10	Session 12	Session 20	Session 24	Session 30	Session 32	Session 42
Venera-16	*Venera-16*	*Venera-15*	*Venera-15*	*Venera-15*	*Venera-16*	*Venera-16*
Oct. 16, 1983	Oct. 17, 1983	Oct. 21, 1983	Oct. 23, 1983	Oct. 25, 1983	Oct. 25, 1983	Oct. 31, 1983
83.9° N, 290.0° W	83.1° N, 296.3° W	83.8° N, 306.9° W	85.3° N, 308.9° W	86.5° N, 310.4° W	88.5° N, 225.3° W	85.5° N, 179.7° W
$Z_\odot = 83.9°$	$Z_\odot = 83.2°$	$Z_\odot = 84.1°$	$Z_\odot = 85.8°$	$Z_\odot = 87.2°$	$Z_\odot = 90.9°$	$Z_\odot = 95.4°$
$h_t = 57.5$ km	$h_t = 57.6$ km	$h_t = 57.3$ km	$h_t = 57.6$ km	$h_t = 57.6$ km	$h_t = 57.4$ km	$h_t = 59.0$ km
$h_{\min} = 58.7$ km	$h_{\min} = 58.7$ km	$h_{\min} = 57.9$ km	$h_{\min} = 58.4$ km	$h_{\min} = 58.4$ km	$h_{\min} = 58.9$ km	$h_{\min} = 59.0$ km

tains an almost instantaneous (frozen) image of the state of the environment in the probed region of the atmosphere of Venus. The frequency variations of the radio occultation signal ($\lambda = 32$ cm) and the known ballistic data of the *Venera-15* and *-16* satellites we previously used to determine the dependences of the refraction angle on the impact parameter of the ray trajectory (Yakovlev et al., 1991). Then, based on the application of the inverse Abel transformation to the vertical profiles of the angle of refraction, the altitude dependences of the refractive index in the neutral atmosphere of the planet were determined. Taking into account the chemical composition of the atmosphere (96.5% CO_2 and 3.5% N_2) made it possible to find vertical density profiles, and using the equations of hydrostatic equilibrium and the gas state, atmospheric pressure and temperature profiles were restored (Yakovlev et al., 1991).

It is convenient to represent the data on the intensity of the radio occultation signal as a function of the altitude of the ray path (the altitude of the ray perigee). Here, the term "ray path" refers to the trajectory of a photon moving from a satellite to a receiving antenna on Earth. The ray perigee altitude as a function of time was determined naturally during processing and analysis of measurements when obtaining atmospheric profiles (Yakovlev et al., 1991). We applied a high-frequency filter to the radio occultation intensity data to separate high-frequency fluctuations from slow background intensity variations. This filter works as follows:

$$i(h) \equiv \frac{I(h) - \langle I(h)\rangle}{\langle I(h)\rangle}. \quad (1)$$

Here, $I(h)$ is the measured signal intensity, h is the ray perigee altitude. Angle brackets denote the local mean calculated on the basis of a polynomial approximation of the second degree of the values of $I(h)$ over an interval of 4 km, the center of which is at a point with altitude h. Since the signal intensity $I(h)$ is a positively defined quantity, the normalized intensity fluctuations $i(h)$ satisfies the inequality $i(h) > -1$. In experiments, powerful bursts of the intensity of the radio occultation signal are often observed, as a result of which the value of $i(h)$ can significantly exceed the value of +1. For this reason, when the values of the modulus $|i(h)|$ approach one, the observed pattern of fluctuations becomes asymmetric about zero (Hinson and Jenkins, 1995).

If the condition ($|i(h)| \ll 1$) for weak scattering is satisfied, fluctuations in the signal intensity $i(h)$ are proportional to fluctuations in the atmospheric density $\rho'(h)$, i.e., $i(h) \propto \rho'(h)$ (Hinson and Tyler, 1983). According to the wave theory, we have (Hinson and Jenkins, 1995):

$$\rho' \propto G_\rho(h)\exp\left[j\int^h m(h)\,dh\right], \quad (2)$$

where $m = 2\pi/\lambda_z$ is the vertical wavenumber, λ_z is the vertical wavelength, j is the imaginary unit, and the amplitude function G_ρ is determined using formula (3), in which ρ_b and N_b are the unperturbed (background) values of atmospheric density and Brunt–Väisälä frequency, respectively; L_r is the vertical scale of the radiative damping length.

$$G_\rho(h) \equiv (\rho_b N_b^3)^{1/2}\exp\left[-\int^h \frac{dh}{L_r(h)}\right]. \quad (3)$$

It follows from relation (3) that in the absence of energy dissipation, the amplitude functions of fluctuations in atmospheric density $\rho'(h)$ and signal intensity $i(h)$ will vary with altitude in proportion to the value $\sqrt{\rho_b(h)}$, but with additional modulation due to vertical variations $\sqrt{N_b^3(h)}$. In the presence of radiative damping in the atmosphere, the change in the amplitude of intensity fluctuations with altitude also depends on the vertical scale of radiative damping L_r, which is related to the radiative relaxation time τ_r by a simple expression (Hinson and Jenkins, 1995):

$$L_r \equiv 2\left|\frac{\omega}{m}\right|\tau_r, \quad (4)$$

where ω is the intrinsic frequency of the internal wave measured in the frame of reference moving with the unperturbed flow (Gubenko et al., 2008b, 2011, 2012, 2015), τ_r is the time of radiative relaxation in the atmosphere of Venus (Fels, 1982). The intrinsic frequency ω and the frequency σ of the internal wave, found in the reference frame of the terrestrial observer, are related by the known relation that determines the Doppler shift between them (Gubenko et al., 2018b; Gubenko and Kirillovich, 2018b):

$$\sigma = \omega + \mathbf{k_h V_b} = \omega + |k_h||V_b|\cos\angle\mathbf{k_h}, \mathbf{V_b}\,, \qquad (5)$$

where $\mathbf{k_h V_b}$ is the scalar product of the horizontal wave vector $\mathbf{k_h}$ and the vector of unperturbed wind speed $\mathbf{V_b}$, $|k_h| = 2\pi/\lambda_h$ is the modulus of the vector $\mathbf{k_h}$, λ_h is the horizontal length of the internal wave, $|V_b|$ is the modulus of the vector $\mathbf{V_b}$.

Figure 2 shows the altitude dependences of the radiative relaxation time $\tau_r(h)$ in the atmosphere of Venus for vertical wavelengths of 5 km (dashed line), 2.5 km (dotted line), and 1 km (solid line), found by extrapolating the results of the Crisp model (1989) for $\lambda_z = 7$ km, assuming that the relaxation time τ_r is proportional to the vertical wavelength λ_z. The $\tau_r(h)$ dependence for the vertical wavelength $\lambda_z = 1$ km we determined in order to analyze the fluctuations of the signal intensity $i(h)$, and the $\tau_r(h)$ profiles for wavelengths of 5 and 2.5 km obtained earlier by Ando et al. (2015, Fig. 7) are shown in Fig. 2 for comparison.

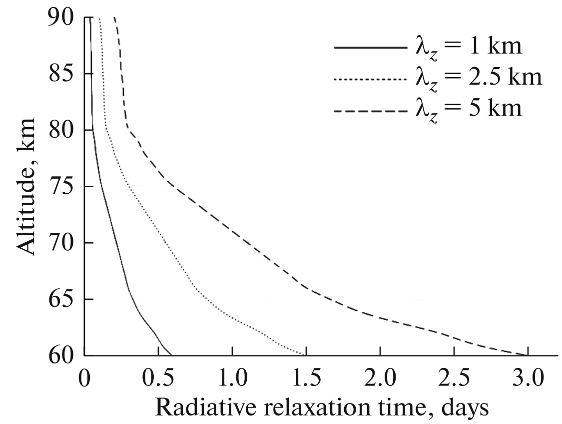

Fig. 2. Altitude profiles of the radiative relaxation time $\tau_r(h)$ in the atmosphere of Venus for vertical wavelengths of 5 km (dashed line), 2.5 km (dotted line), and 1 km (solid line), found by extrapolating the results of the Crisp (1989) model for the vertical wavelength $\lambda_z = 7$ km, assuming that τ_r is proportional to λ_z.

Figures 3–5 show examples of the profiles of high-frequency fluctuations (scintillations) of the signal intensity $i(h)$ observed in radio occultation sessions 24, 30, and 42 (jagged lines). The altitude of the ray trajectory is measured here from the mean surface level of the planet with a radius of 6051 km. The most high-frequency scintillations caused by small-scale inhomogeneities of the refractive index (density) in the atmosphere of Venus are diffraction effects. As follows from the results of Gubenko et al. (2008a), the diffraction pattern in the polar atmosphere of Venus at altitudes near the tropopause is formed by inhomogeneities with vertical sizes less than the radius of the first Fresnel zone (~0.32 km). Signal intensity fluctuations recorded in radio occultation experiments, the vertical size of which exceeds the Fresnel radius, are not associated with diffraction and may be due to the influence of regular thin layers or internal atmospheric waves (Gubenko et al., 2008a). In contrast to analog measurements of the signal frequency, which was determined once per second, radio occultation measurements of the intensity were carried out with a sufficiently high sampling frequency of ~19 Hz. In this case, the vertical resolution δh of the data on the intensity of the radio occultation signal at the tropopause level in the atmosphere of Venus is determined by the vertical size of the Fresnel zone (radius). Taking into account the refractive attenuation of the signal, we obtain the following estimate of the vertical resolution for the analyzed data on the intensity: $\delta h = r_f \langle X\rangle^{1/2} = (\lambda L\langle X\rangle)^{1/2} \approx 0.32$ km (Gubenko et al., 2008a). Here, $r_f = (\lambda L)^{1/2} \approx 1$ km is the radius of the first Fresnel zone in free space outside the atmosphere, $\lambda = 0.32$ m is the signal wavelength, $L \approx 3470$ km is the distance from the satellite to the planet limb, $\langle X\rangle = \langle I(h)\rangle \approx 0.1$ is the local average value of the refractive attenuation (of intensity) of the radio occultation signal near the tropopause level in the atmosphere of Venus. Such a high vertical resolution was achieved due to the rather high sampling frequency of radio occultation measurements of the radio wave intensity, as well as due to the significant compression of the Fresnel volume of the beam in the vertical direction due to the effect of refractive attenuation of the signal intensity.

The method for determining the dominant vertical scale λ_z is described in detail in (Gubenko et al., 2008a), and its essence is as follows. At the altitude interval from ~61.5 to ~70.0 km, using the fast Fourier transform, the power spectra of signal intensity fluctuations for the analyzed sessions were found, and the maximum of the spectral spatial frequency was determined. It was found that at altitudes above ~61.5 km, where the effects of radiative damping in the atmosphere become noticeable, the dominant vertical size of intensity fluctuations λ_z is ~1 km.

Since there is no vertical correlation of fluctuations recorded in different measurement sessions (close in location and time), these fluctuations are likely due to small-scale IGWs rather than regular layers in the atmosphere (Gubenko et al., 2008a). Smooth dashed lines in Figs. 3–5 show how the amplitude functions $G_\rho(h)$ change with altitude in sessions 24, 30, and 42 according to the wave theory (including the effect of

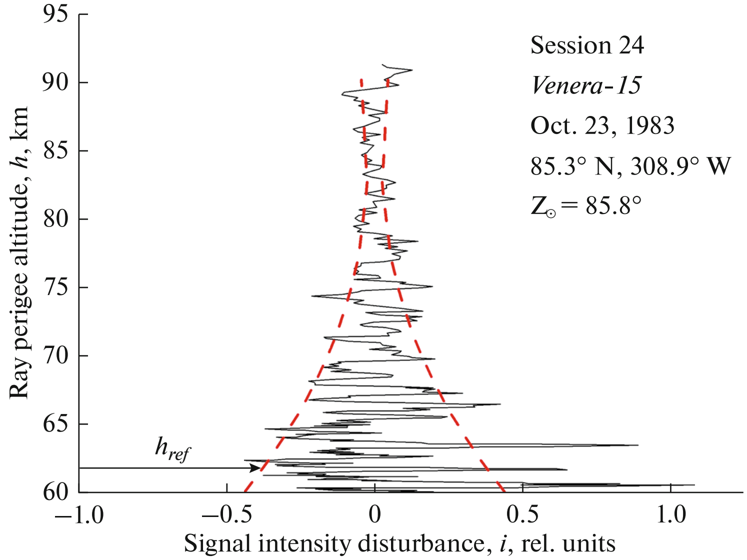

Fig. 3. Normalized fluctuations of the signal intensity $i(h)$ observed in the radio occultation session 24 of measurements of the *Venera-15* satellite (jagged line). The smooth dashed line shows how the amplitude function $G_\rho(h)$ changes with altitude according to wave theory (including the effect of radiative damping). The vertical scale of the length L_r of radiative damping in the Venusian atmosphere is $L_r = 8700$ m ($h_{ref} = 61.8$ km) for session 24.

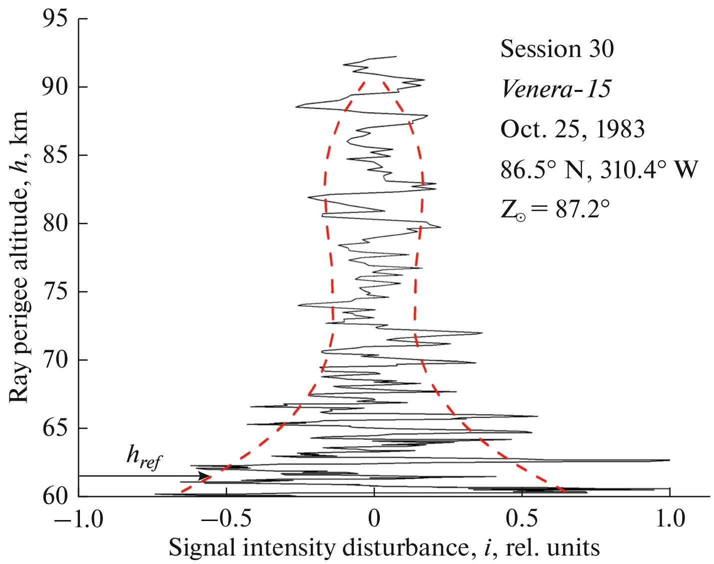

Fig. 4. Altitude profile of high-frequency fluctuations of the signal intensity $i(h)$, obtained in the radio occultation session 30 of measurements of the *Venera-15* satellite (jagged line). The vertical scale of the length L_r of radiative damping in the planet's atmosphere is $L_r = 6500$ m ($h_{ref} = 61.5$ km) for session 30.

radiative damping). To determine the vertical scale of the radiative damping length L_r in the analyzed measurement session, it is necessary to select from the profile of the amplitude function $G_\rho(h)$ the "pure" effect associated with radiative damping of intensity fluctuations in the atmosphere. We used the previously obtained results of reconstructing the average profiles of density $\rho_b(h)$ and Brunt–Väisälä frequency $N_b(h)$ (Yakovlev et al., 1991) to calculate the correcting function $k(h)$:

$$k(h) = \sqrt{\frac{\rho_b(h_{\rm ref})N_b^3(h_{\rm ref})}{\rho_b(h)N_b^3(h)}}, \tag{6}$$

where $h_{\rm ref}$ is the initial reference altitude at the bottom of the measurement session. The corrected amplitude function $G_\rho^*(h) = G_\rho(h)k(h)$ is determined only by the vertical scale of the length L_r of radiative damping of fluctuations in the atmosphere and does not depend on changes in $\rho_b(h)$ and variations in $N_b(h)$ with alti-

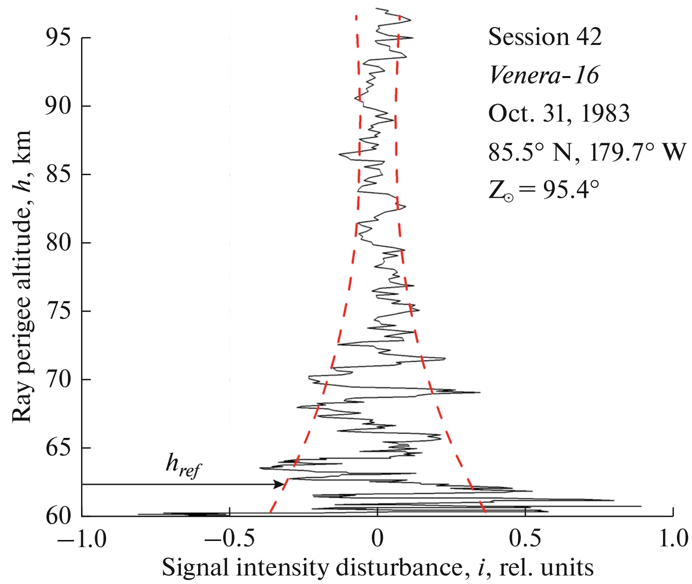

Fig. 5. Vertical profile of normalized fluctuations of signal intensity $i(h)$ observed in the radio occultation session 42 of measurements of the *Venera-16* satellite (jagged line). The L_r value is $L_r = 12000$ m ($h_{ref} = 62.3$ km) for session 42.

tude. Taking into account relations (3) and (6), it is easy to see that the expression for the corrected amplitude function $G_\rho^*(h)$ has the following form:

$$G_\rho^*(h) \equiv G_\rho(h)k(h)$$
$$\equiv \left[\rho_b(h_{\mathrm{ref}})N_b^3(h_{\mathrm{ref}})\right]^{1/2}\exp\left[-\int^{h}\frac{dh}{L_r(h)}\right]. \quad (7)$$

Correction of the amplitude functions $G_\rho(h)$ shown in Figs. 3–5 as smooth dashed lines in this way allows us to determine the corresponding functions $G_\rho^*(h)$. An analysis of the amplitude profile makes it possible to find the length of the interval in which the corrected fluctuation amplitude decreases by a factor of e. The indicated length determines the vertical scale L_r for the radiative damping of signal intensity fluctuations in the atmosphere of Venus. Taking into account the real vertical resolution of the radio occultation data (~430 m) and the found values of the parameter L_r (see Table 2), it can be concluded that the relative error in the reconstruction of L_r does not exceed 10%. Thus, we found the following values of the vertical scale L_r for the analyzed sessions: $L_r = 8700$ m ($h_{ref} = 61.8$ km, Fig. 3) for session 24; $L_r = 6500$ m ($h_{ref} = 61.5$ km, Fig. 4) for session 30; $L_r = 12000$ m ($h_{ref} = 62.3$ km, Fig. 5) for session 42.

The key characteristics of internal gravity waves in the polar atmosphere of Venus, obtained from the analysis of seven radio occultation sessions of measuring the signal intensity ($\lambda = 32$ cm) of the *Venera-15* and *-16* satellites, are given in Table 2. The method for calculating the wave parameters is based on the use of formula (4). First, according to the results of the analysis of the vertical profile of the signal intensity fluctuations, the vertical scale L_r of the radiative damping for the given measurement session is determined. At the next stage, the time of radiative relaxation in the Venusian atmosphere τ_r is calculated for the analyzed intensity fluctuations with the vertical wavelength $\lambda_z = 1$ km, localized in a given altitude interval (see Fig. 2). Then, using expression (4), the intrinsic frequency ω of the identified internal wave is determined. Further, based on the dispersion equation $\omega/N_b = |k_h|/|m| = \lambda_z/\lambda_h$ for internal waves in the interval of intermediate intrinsic frequencies ($f^2 \ll \omega^2 \ll N_b^2$) and the conservative estimate of the unperturbed Brunt–Väisälä frequency $N_b = 0.02$ rad/s, the horizontal wavelength λ_h is found. At the last stage, the intrinsic horizontal ($\left|c_{ph}^{in}\right| = \omega/\left|k_h\right|$) and vertical ($\left|c_{pz}^{in}\right| = \omega/\left|m\right|$) phase velocities are determined, as well as the intrinsic period ($\tau_i = 2\pi/\omega$) for the IGW (Gubenko et al., 2008b, 2011, 2012, 2015, 2018b). When calculating the wave characteristics, we used the value of the radiative relaxation time τ_r, which corresponds to the altitude h_{ref} at the lower measurement boundary. Therefore, the IGW parameter values given in Table 2 refer to the initial altitude h_{ref} for the analyzed radio occultation session. The developed model for the radiative damping of intensity fluctuations with altitude in the atmosphere of Venus assumes that the intrinsic frequencies for the identified internal atmospheric waves in the sessions under study vary from 3.5×10^{-4} to 9.5×10^{-4} rad/s, and the ratio of the horizontal and vertical wavelengths is in the range from 57 to 21. The intrinsic periods of

Table 2. Characteristics of IGWs in the atmosphere of Venus, obtained from the analysis of seven sessions of radio occultation measurements of the signal intensity

Session number	h_{ref}, km	L_r, m	τ_r, s	$L_r/(2\tau_r)$, m/s	ω, rad/s	τ_i, hour	N_b, rad/s	λ_z, m	λ_h, m	$\left\|c_{ph}^{in}\right\|$, m/s	$\left\|c_{pz}^{in}\right\|$, m/s
10	62.2	4.6×10^3	41.0×10^3	0.056	3.5×10^{-4}	5.0	2.0×10^{-2}	$\sim 10^3$	57×10^3	3.2	5.6×10^{-2}
12	63.0	5.2×10^3	36.7×10^3	0.071	4.5×10^{-4}	3.9	2.0×10^{-2}	$\sim 10^3$	44×10^3	3.2	7.1×10^{-2}
20	62.4	8.4×10^3	39.8×10^3	0.106	6.6×10^{-4}	2.6	2.0×10^{-2}	$\sim 10^3$	30×10^3	3.2	10.6×10^{-2}
24	61.8	8.7×10^3	43.2×10^3	0.101	6.3×10^{-4}	2.8	2.0×10^{-2}	$\sim 10^3$	32×10^3	3.2	10.1×10^{-2}
30	61.5	6.5×10^3	44.3×10^3	0.073	4.6×10^{-4}	3.8	2.0×10^{-2}	$\sim 10^3$	43×10^3	3.2	7.3×10^{-2}
32	62.3	12.2×10^3	40.1×10^3	0.152	9.5×10^{-4}	1.8	2.0×10^{-2}	$\sim 10^3$	21×10^3	3.2	15.2×10^{-2}
42	62.3	12.0×10^3	40.1×10^3	0.150	9.4×10^{-4}	1.9	2.0×10^{-2}	$\sim 10^3$	21×10^3	3.2	15×10^{-2}

IGWs are from 1.8 to 5 h, and the horizontal wavelengths vary within 21–57 km (see Table 2).

Earlier, Hinson, and Jenkins (1995), analyzing signal intensity scintillations in the Magellan radio occultation experiment, found that the measured vertical profile of intensity variations is consistent with IGWs freely propagating in the atmosphere without wind shear. They found that the internal waves that cause these intensity scintillations have vertical wavelengths of ~1 km and horizontal phase velocities of ~3 m/s. Comparison between theory and observations showed that $\omega\tau_r \approx 70$ at an altitude of 65 km. The obtained value of $\omega\tau_r$ is about five times greater than for the internal wave ($\lambda_z \approx 2.5$ km), found from the analysis of temperature measurements of the Magellan mission. This suggests that the intrinsic frequency ω of small-scale IGWs is also several times higher than the frequency ($\omega = 2 \times 10^{-4}$ rad/s) of the wave mentioned above. Note that the error in reconstructing wave characteristics in the Magellan experiment is ~50% (Hinson and Jenkins, 1995).

Comparison of our results with those obtained in (Hinson and Jenkins, 1995) shows that IGWs, which cause scintillations of the signal intensity in the radio occultation experiments of the *Magellan* and *Venera-15*, *-16* satellites, have approximately the same horizontal phase velocity (3–3.2 m/s) and vertical wavelength (~1 km). Based on the results of the analysis of seven measurement sessions, it was found that the value of $\omega\tau_r$ at an altitude of ~62 km lies in the range from ~14 to ~38. In this case, the intrinsic frequencies of the identified IGWs varied from ~3.5×10^{-4} to ~9.5×10^{-4} rad/s, which, taking into account the errors in reconstructing the wave characteristics, agrees with the results obtained in (Hinson and Jenkins, 1995).

Based on the results of radio occultation measurements of *Venera-15* (session 30), Gubenko et al. (2008a) compared the thermal and small-scale structures of Venus's atmosphere at altitudes from 58.0 to 77.0 km. Figure 7 of (Gubenko et al., 2008a) shows the vertical profiles of temperature (left panel), temperature variations (middle panel), and normalized fluctuations of signal amplitude (right panel). The results of temperature reconstruction from one-second data on the signal frequency (range λ = 32 cm) are shown by dots. The vertical resolution of experimental data on temperature is characterized by the size of the sampling interval for the temperature profile (the vertical distance between adjacent points) and is nonuniform at different levels. Here it is determined by the vertical velocity of the descent of the radio ray and varies from ~0.4 km at an altitude of ~59 to ~1.1 km at ~65 km. For a correct comparison with the temperature data, the initial amplitude data were averaged using the moving average method in one-second intervals. The temperature and signal amplitude profiles shown in Fig. 7 (Gubenko et al., 2008a) demonstrate quasi-periodic variations with a vertical length from ~3.1 to ~4.0 km at altitudes from ~59 to ~65 km. The amplitude of the wavelike temperature variations is approximately constant in the indicated altitude interval and is ~1.5 K. Note that the vertical resolution of the analyzed temperature data is insufficient to detect the influence of the small-scale structure of the atmosphere (IGWs with a vertical wavelength of ~1 km) on the temperature profiles in the atmosphere of Venus.

Imamura et al. (2018) applied the Full Spectrum Inversion (FSI) method to the radio occultation data from the *Venus Express* and *Akatsuki* missions in order to reconstruct small-scale structures in the Venusian atmosphere at cloud level. The FSI temperature profiles have a vertical resolution of ~150 m, which is much better than the typical resolution of ~400–700 m for geometric optics. Application of this radio holographic method to radio occultation data allows us to resolve fine atmospheric structures (including those in multiray zones), which are not reproduced when analyzing measurements by geometric optics methods.

CONCLUSIONS

The radio occultation measurements of the signal intensity (λ = 32 cm) of the *Venera-15* and *-16* satellites, carried out in the period from October 16 to October 31, 1983, are used to analyze the activity of internal waves in the northern polar atmosphere of Venus. Observations of the intensity of radio waves provide important information about the fine-scale structure of the atmosphere. A comparison of radio occultation measurements and the results of the standard wave theory shows that small-scale fluctuations of the received signal intensity are caused by propagating IGWs with a vertical wavelength of ~1 km at altitudes above 61.5 km. The developed model of radiative damping of intensity fluctuations with altitude in the atmosphere of Venus assumes that the intrinsic frequencies for the identified internal atmospheric waves in the sessions under study vary from 3.5×10^{-4} to 9.5×10^{-4} rad/s, and the ratio of the horizontal and vertical wavelengths is in the range from 57 to 21. Intrinsic periods of IGWs are from 1.8 to 5 hours, and horizontal wavelengths vary from 21 to 57 km.

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REFRERENCES

Ando, H., Imamura, T., Tsuda, T., Tellmann, S., Patzold, M., and Hausler, B., Vertical wavenumber spectra of gravity waves in the Venus atmosphere obtained from Venus Express radio occultation data: Evidence for saturation, *J. Atmos. Sci.,* 2015, vol. 72, pp. 2318–2329. https://doi.org/10.1175/JAS-D-14-0315.1

Crisp, D., Radiative forcing of the Venus mesosphere. II. Thermal fluxes, cooling rates, and radiative equilibrium temperatures, *Icarus,* 1989, vol. 77, pp. 391–413.

Fels, S.B., A parameterization of scale-dependent radiative damping grace in the middle atmosphere, *J. Atmos. Sci.,* 1982, vol. 39, pp. 1141–1152.

Gubenko, V.N. and Andreev, V.E., Radio wave fluctuations and layered structure of the upper region of Venusian clouds from radio occultation data, *Cosmic Res.,* 2003, vol. 41, no. 2, pp. 135–140.

Gubenko, V.N. and Kirillovich, I.A., The study of zonal circulation of Venus's atmosphere by data analysis of radio occultation measurements made by Venera-15 and -16 satellites, *Cosmic Res.,* 2018a, vol. 56, no. 6, pp. 471–479. https://doi.org/10.1134/S0010952518060047

Gubenko, V.N. and Kirillovich, I.A., Diagnostics of internal atmospheric wave saturation and determination of their characteristics in Earth's stratosphere from radiosonde measurements, *Sol.-Terr. Phys.,* 2018b, vol. 4, no. 2, pp. 41–48. https://doi.org/10.12737/stp-42201807

Gubenko, V.N. and Kirillovich, I.A., Modulation of sporadic E layers by small-scale atmospheric waves in Earth's high-latitude ionosphere, *Sol.-Terr. Phys.,* 2019, vol. 5, no. 3, pp. 98–108. https://doi.org/10.12737/stp-53201912

Gubenko, V.N., Andreev, V.E., and Pavelyev, A.G., Detection of layering in the upper cloud layer of Venus northern polar atmosphere observed from radio occultation data, *J. Geophys. Res.,* 2008a, vol. 113. https://doi.org/10.1029/2007JE002940

Gubenko, V.N., Pavelyev, A.G., and Andreev, V.E., Determination of the intrinsic frequency and other wave parameters from a single vertical temperature or density profile measurement, *J. Geophys. Res.,* 2008b, vol. 113, no. D08109. https://doi.org/10.1029/2007JD008920

Gubenko, V.N., Kirillovich, I.A., and Pavelyev, A.G., Characteristics of internal waves in the Martian atmosphere obtained on the basis of an analysis of vertical temperature profiles of the Mars global surveyor mission, *Cosmic Res.,* 2015, vol. 53, no. 2, pp. 133–142. https://doi.org/10.1134/S0010952515020021

Gubenko, V.N., Kirillovich, I.A., Liu, Y.-A., Pavelyev, A.G., Monitoring of the activity of internal gravity waves in the atmosphere of the Arctic and Antarctic, *Izv. VUZov, Fiz.,* 2016b, vol. 59, no. 12-3, pp. 80–85.

Gubenko, V.N., Kirillovich, I.A., Pavelyev, A.G., and Andreev, V.E., Detection of saturated internal gravity waves and reconstruction of their characteristics in the atmosphere of Mars, *Izv. VUZov, Fiz.,* 2016a, vol. 59, no. 12-2, pp. 46–49.

Gubenko, V.N., Matyugov, S.S., Yakovlev, O.I., and Vaganov, I.R., Zonal wind in the southern polar regions of Venus according to radio transillumination data, *Kosm. Issled.,* 1992, vol. 30, no. 3, pp. 390–395.

Gubenko, V.N., Pavelyev, A.G., Andreev, V.E., Kirillovich, I.A., and Salimzyanov, R.R., Radio occultation studies of internal waves and layered structures in the atmospheres of Earth, Mars, and Venus, in *Sovremennye dostizheniya v plazmennoi geliogeofizike* (Current Advances in Plasma Heliogeophysics), Zelenyi, L.M., Petrukovich, A.A., and Veselovskii, I.S., Eds., Moscow: Fizmatlit, 2018a.

Gubenko, V.N., Pavelyev, A.G., Kirillovich, I.A., and Liou, Y.-A., Case study of inclined sporadic E layers in the Earth's ionosphere observed by CHAMP/GPS radio occultations: Coupling between the tilted plasma layers and internal waves, *Adv. Space Res.,* 2018b, vol. 61, no. 7, pp. 1702–1716. https://doi.org/10.1016/j.asr.2017.10.001

Gubenko, V.N., Pavelyev, A.G., Salimzyanov, R.R., and Andreev, V.E., A method for determination of internal gravity wave parameters from a vertical temperature or density profile measurement in the Earth's atmosphere, *Cosmic Res.,* 2012, vol. 50, no. 1, pp. 21–31. https://doi.org/10.1134/S0010952512010029

Gubenko, V.N., Pavelyev, A.G., Salimzyanov, R.R., and Pavelyev, A.A., Reconstruction of internal gravity wave parameters from radio occultation retrievals of vertical temperature profiles in the Earth's atmosphere, *Atmos. Meas. Tech.,* 2011, vol. 4, no. 10, pp. 2153–2162. https://doi.org/10.5194/amt-4-2153-2011

Gubenko, V.N., Yakovlev, O.I., and Matyugov, S.S., Radio occultation measurements of the radio wave absorption and the sulfuric acid vapor content in the atmosphere of

Venus, *Cosmic Res.,* 2001, vol. 39, no. 5, pp. 439–445. https://doi.org/10.1023/A:1012336911928

Hinson, D.P. and Jenkins, J.M., Magellan radio occultation measurements of atmospheric waves on Venus, *Icarus,* 1995, vol. 114, pp. 310–327.

Hinson, D.P. and Tyler, G.L., Internal gravity waves in Titan's atmosphere observed by Voyager radio occultation, *Icarus,* 1983, vol. 54, pp. 337–352.

Imamura, T., Miyamoto, M., Ando, H., Hausler, B., Patzold, M., Tellmann, S., Tsuda, T., Aoyama, Y., Murata, Y., Takeuchi, H., Yamazaki, A., Toda, T., and Tomiki, A., Fine vertical structures at the cloud heights of Venus revealed by radio holographic analysis of Venus Express and Akatsuki radio occultation data, *J. Geophys. Res.: Planets,* 2018, vol. 123, pp. 2151–2161.

Matyugov, S.S., Gubenko, V.N., Yakovlev, O.I., and Vaganov, I.R., The atmosphere of Venus at mid-latitudes according to radio transillumination data, *Kosm. Issled.,* 1994, vol. 32, no. 3, pp. 108–114.

Tellmann, S., Hausler, B., Hinson, D.P., Tyler, G.L., Andert, T.P., Bird, M.K., Imamura, T., Patzold, M., and Remus, S., Small-scale temperature fluctuations seen by the VeRa radio science experiment on Venus Express, *Icarus,* 2012, vol. 221, pp. 471–480. https://doi.org/10.1016/j.icarus.2012.08.023

Vaganov, I.R., Yakovlev, O.I., Matyugov, S.S., and Gubenko, V.N., Wind in the northern polar atmosphere of Venus, *Kosm. Issled.,* 1992, vol. 30, no. 5, pp. 695–699.

Yakovlev, O.I., Matyugov, S.S., and Gubenko, V.N., Venera-15 and -16 middle atmosphere profiles from radio occultations: Polar and near-polar atmosphere of Venus, *Icarus,* 1991, vol. 94, no. 2, pp. 493–510. https://doi.org/10.1016/0019-1035(91)90243-M

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