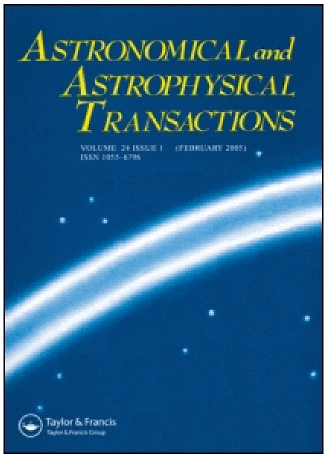

Astronomical & Astrophysical Transactions
The Journal of the Eurasian Astronomical Society
Publication details, including instructions for authors and subscription information:
http://www.informaworld.com/smpp/title~content=t713453505

The identification of the fluctuation effects related to the turbulence and "permanent" layers in the atmosphere of Venus from radio occultation data

V. N. Gubenko [a]; V. E. Andreev [a]
[a] Institute of Radio Engineering and Electronics, Russian Academy of Sciences, Russia

To cite this Article: Gubenko, V. N. and Andreev, V. E. (2007) 'The identification of the fluctuation effects related to the turbulence and "permanent" layers in the atmosphere of Venus from radio occultation data', Astronomical & Astrophysical Transactions, 26:6, 507 - 515
To link to this article: DOI: 10.1080/10556790701610399
URL: http://dx.doi.org/10.1080/10556790701610399

Astronomical and Astrophysical Transactions
Vol. 26, No. 6, December 2007, 507–515

The identification of the fluctuation effects related to the turbulence and "permanent" layers in the atmosphere of Venus from radio occultation data

V. N. GUBENKO and V. E. ANDREEV*

Institute of Radio Engineering and Electronics, Russian Academy of Sciences, Russia

(Received 19 July 2007)

The results of cross-correlation analysis of the amplitude fluctuations of radio waves of the $\lambda = 32$ cm band in seven sessions of radio occultation measurements of the northern polar atmosphere of the planet are presented. The existence of the cross-correlation of fluctuations ($b_\chi \simeq 0.6$–0.7) is established in the altitude realizations in the interval 61.5–65.0 km for four different sessions of radio occultations. Inner layering is revealed in the upper layer of the clouds of the planet at altitudes of 61.5–65.0 km, which is specified by an enhanced turbulence of the atmosphere. It is found that the "lifetime" of the small-scale layered irregularities is no less than two days and that their horizontal extension in the meridional direction can exceed ~130 km. A possible cause of the emergence of the layered structures inside the upper layer of the polar clouds of Venus is discussed.

Keywords: Scintillation; Radio sounding; Planet atmosphere

1. Introduction

The fluctuations of radio waves observed in the radio occultation of the Venusian atmosphere allow one to investigate adequately the spatial irregularities of the atmosphere of this planet. Earlier, it was discovered in radio occultation experiments carried out by the spacecrafts *Mariner-5*, *Mariner-10*, *Venera-9*, and *Pioneer Venus Orbiter* that the variance of fluctuations of the logarithm of the signal's amplitude received on Earth appreciably increases during the passage of the radio ray at altitudes of about 60 km above the Venusian surface [1–4]. The authors of these papers suggested that the observed increase of the intensity of the amplitude fluctuations is due to the effect of turbulence, which takes place in the atmosphere at altitudes of about 60 km. The argument in favour of this hypothesis is the fact that the shapes of frequency spectra of the amplitude's logarithm have a form typical for the case of propagation of radio waves in a turbulent medium with a power-law spectrum of irregularities. The region of the atmosphere at altitudes of about 60 km, where the increase of the intensity of radio wave

---

*Corresponding author. Email: vitali-a@mail.ru

Astronomical and Astrophysical Transactions
ISSN 1055-6796 print/ISSN 1476-3540 online © 2007 Taylor & Francis
http://www.tandf.co.uk/journals
DOI: 10.1080/10556790701610399

fluctuations in the occultation measurements was observed, it was referred to as the "upper region of turbulence".

The typical parameters of irregularities and possible mechanisms of the emergence of atmospheric turbulence at altitudes of about 60 km were analysed in [3]. A comparison of the theoretical and experimental spectra of fluctuations of the logarithm of the amplitude revealed that the best coincidence of these spectra is obtained in the case when turbulent irregularities are anisotropic and strongly elongated in the horizontal direction (the axial ratio $\geq$10). It was also established that the upper region of turbulence coincided with the region of the atmosphere that is stable with respect to convection, where one or several local maxima in the altitude profiles of stability existed. Since in the regions of the local maxima of stability the capture of the inner gravitational waves is possible, whose spectrum, it is assumed, is close to the Kolmogorov spectrum, it is very likely that the turbulence in the upper region is due to the effect of inner gravitational waves [3].

The analysis of the available data related to the temperature and velocity of the wind at altitudes of about 60 km demonstrates that the local convection of the atmosphere or the vertical gradients of the wind velocity cannot be a cause of the emergence of the turbulence and, as a consequence of it, of the amplitude fluctuations of radio waves in the occultation measurements. The authors of [3] argue that precisely the capture of gravitational waves, which leads to the emergence of the turbulence of the atmosphere in the upper region, explains the observed fluctuations of the amplitude in radio occultation measurements.

Nonetheless, it is not inconceivable that, along with the atmospheric turbulence, another cause of the emergence of the observed amplitude fluctuations is the stable layers in the Venusian atmosphere. The upper region of turbulence is inside the upper layer of the clouds of the planet. The layering in the upper region of the clouds of the Venusian atmosphere was observed in the altitude profiles of the coefficient of back-scattering obtained from the data of nephelometric measurements onboard the spacecrafts *Venera-9*, *Venera-10*, and *Venera-14* [5]. The layering was also observed above 57–58 km in the altitude dependencies of the cross-sections of back-scattering for the day and large probes of the *Pioneer Venus* spacecraft [6].

The role of the permanent layers in the formation of the observed fluctuations of the amplitude was discussed in [3]. With this aim, the comparison of the occultation measurement sessions closest with respect to time (an interval of 24 h), in which the regions under investigation were located at a distance of about 100 km, was made. It was established for the upper region of turbulence that the fluctuations of radio waves in the closest occultation sessions are only statistically similar and do not duplicate each other in detail. Because of this the authors of [3] concluded that the observed fluctuations mainly represent random turbulence and not permanent layers.

We think that such conclusion is not sufficiently convincing. The point is that the authors of [3] had at their disposal information concerning the geometrical parameters (i.e., the components of the satellite's velocity and altitude as functions of time) only for a single occultation measurement session ([3], pp. 8034–8035). Only a comparison of the time realizations of the amplitude's fluctuations for different occultation sessions can be carried out in this case. However, the result of such a comparison is ambiguous even if in different occultation measurements the same atmospheric structure is sounded (for example, a stable layer), since this result depends on the relation between the vertical components of the ray velocities in the sessions to be compared.

Therefore, in order to identify correctly the fluctuation effects related to the permanent layers in the Venusian atmosphere, it is necessary to compare the altitude realizations of the amplitude fluctuations, which automatically take into account possible differences of the vertical components of the ray velocities in different occultation measurement sessions.

The goal of this paper is the presentation and cross-correlation analysis of the experimental data related to the amplitude fluctuations of the radio waves of the 32 cm band in seven sessions of radio occultations of the Venusian atmosphere. The experiments were carried out in the period from 16 October to 31 October, 1983, in seven adjacent northern regions with latitudes $>83°$ onboard the *Venera-15* and *Venera-16* spacecrafts. We proceed in representing our data from the value of the mean Venusian radius $a = 6051$ km.

2. Experimental data

Let us consider the variations of the field strength of decimeter radio waves ($\lambda = 32$ cm) during the radio occultation of the polar atmosphere of the Venusian northern hemisphere. Indented curves in figure 1(a,b) represent typical variations of the normalized amplitude $E(h)$ of the signal versus the altitude h of the ray above the surface obtained correspondingly in the 24th and 30th sessions of the radio sets of the satellite *Venera-15* behind the planet. The smoothed curves here, which represent the mean variations of the field strength $E_0(h)$ in the range of altitudes from 58 to 90 km, were obtained using the experimental data of $E(h)$ by the least squares method. The amplitude was normalized in such manner that the passage of the radio wave outside the limits of the atmosphere ($h > 90$ km) corresponds to the unit mean level of the normalized amplitude of the radio signal. The measurements corresponding to sessions 24 and 30 were carried out on 23 and 25 October, 1983 (with an interval of 49 h). The region of the atmosphere investigated on 23 October was located at latitude 85.3°N and longitude 308.9°W

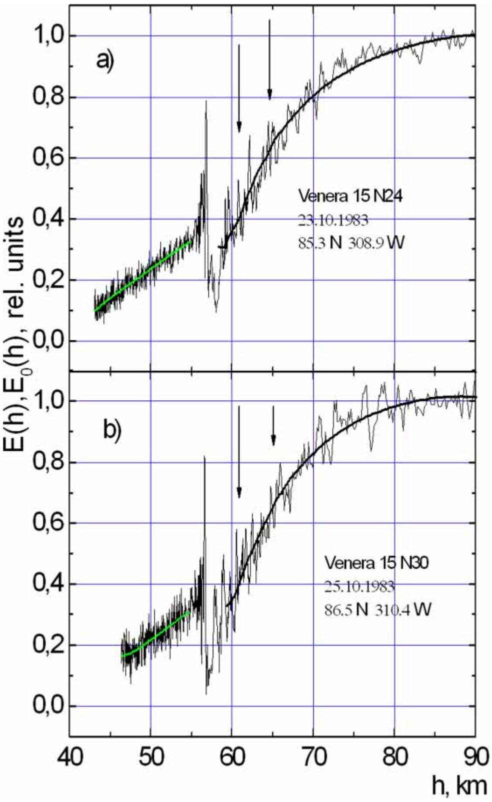

Figure 1. Experimental dependences of the field strength on the minimal altitude of the ray in the 24th and 30th sessions of radio occultation.

and the coordinates of the region sounded during session 30 were the following: latitude 86.5°N and longitude 310.4°W. At an altitude of about 60 km the horizontal separation of the atmospheric structures with the coordinates cited above was 128 km along the meridian line and 18 km along the latitude circle.

The time variations of the frequency and amplitude of radio waves were recorded during the radio occultation of the Venusian atmosphere. In order to relate the amplitude data to the minimal altitude h of the ray above the surface of the planet, the results of the signal's processing were used, taking into account the trajectory of the satellite's motion, which allowed us to determine the dependence $h(t)$. Second-to-second measurements of the frequency made it possible to relate the amplitude of the signal recorded approximately 19 times per second to the "nodal" values of the minimal altitude of the ray above the surface. The altitudes corresponding to the amplitudes between the "nodes" were deduced by linear interpolation. It was demonstrated in [7] that the accuracy of the altitude referencing is mainly determined by the errors of method in the altitude reconstruction, which, as a rule, do not exceed ± 0.3 km for the radio occultation sessions which we consider.

Despite the two-day time interval between the measurements and spatial separation of the atmosphere regions investigated, the dependencies $E(h)$ presented in figure 1(a,b) have a general similarity. For example, in the interval of altitudes from 85 to 60 km, against the background of decreasing mean field strength when altitude h decreases, fluctuations of the signal level due to the irregularities of the atmosphere were observed. The behaviour of the amplitude is specified by a dramatic peculiarity when the radio ray passes through altitudes of 59–57 km. According to [7], at these altitudes in the polar atmosphere of the planet's northern hemisphere, the region of the tropopause is located, which separates the isothermal atmosphere situated higher and underlying the adiabatic atmosphere with an almost constant vertical gradient of temperature. Here, in a narrow interval of altitudes of 59–57 km, where the temperature gradients change greatly [7], successive alternation of deep minima and sharp maxima of the radio wave field strength is observed. The existence of this dramatic peculiarity in the behaviour of the amplitude is permanent in radio occultations at the high latitudes considered by us. Let us also note that the authors of [3] in their analysis of turbulence had eliminated from consideration the regular peculiarity of the amplitude at an altitude of about 60 km, correctly reasoning that it is not associated with the upper region of turbulence located somewhat higher than 60 km.

In order to search for regular atmospheric structures in the upper region of turbulence, a detailed mutual comparison in altitude of the amplitude fluctuations observed in seven different radio occultations of the polar atmosphere of the planet was carried out. For this purpose we used the fluctuations of the amplitude $\chi(h) = ln(E(h)/E_0(h))$, where $E(h)$ is the value of the field strength corresponding to the minimal altitude of the ray above the surface and $E_0(h)$ is the polynomial value of the function approximating the mean level of the field strength for the altitude h of the ray. When the fluctuations are weak, as in our case, the characteristic χ coincides with the normalized estimate of the amplitude fluctuations, which is called the depth of fading of the field strength $\eta = \Delta E(h)/E_0(h) = (E(h) - E_0(h))/E_0(h)$.

To show the high correlation between the fluctuations in different occultation sessions more clearly, the altitude series of the amplitude have been detrended. As an example, figure 2 presents a pair of dependences $\chi(h) = ln(E(h)/E_0(h)) \approx \Delta E(h)/E_0(h)$ specifying the altitude interval 61.5–65.0 km. They were obtained in the 24th (dotted line) and 30th (solid line) sessions of radio occultations of the atmosphere. One can notice that in the dependences $\chi_1(h)$ and $\chi_2(h)$ in figure 2 there is a significant correlation of the amplitude fluctuations detected in different regions of the atmosphere with the time interval of 49 h. A particularly neat correspondence with respect to the altitude is demonstrated by the spectacular details of the amplitude fluctuations near the levels of 62.0 and 64.5 km.

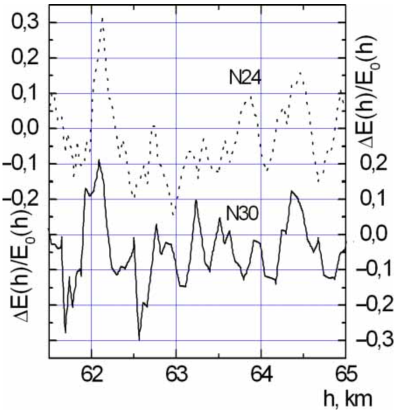

Figure 2. Altitude dependences of the normalized fluctuations of the amplitude in the interval 61.5–65.0 km observed in the sounding of two polar regions of the atmosphere (N24 (85.3N, 308.9W) – 23.10.1983; N30 (86.5N, 310.4W) – 25.10.1983).

As a quantitative characteristic of the degree of correlation of dependences $\chi_1(h)$ and $\chi_2(h)$ presented in figure 2, we take the coefficient of cross-correlation [8]

$$b_\chi = \frac{\langle\chi_1\chi_2\rangle - \langle\chi_1\rangle\langle\chi_2\rangle}{\left[\langle\chi_1^2\rangle - \langle\chi_1\rangle^2\right]^{1/2}\left[\langle\chi_2^2\rangle - \langle\chi_2\rangle^2\right]^{1/2}}$$

The values of the cross-correlation coefficient b_χ of the amplitude fluctuations in the different sessions of radio measurements in the altitude interval 61.5–65.0 km are represented in table 1.

The session coordinates are also indicated. It follows from table 1 that the amplitude fluctuations detected in the 24th and 30th sessions of radio measurements in the interval of h from 61.5 to 65.0 km demonstrate a high degree of correlation characterized by the value $b_\chi \simeq 0.6$. This table also demonstrates that in the 24th and 28th sessions the maximum of the cross-correlation coefficient $b_\chi \simeq 0.7$ is achieved.

We also searched for cross-correlation of the amplitude fluctuations in other pairs of sessions in the altitude intervals having different extensions and located within the limits of the upper region of turbulence. The circumstances due to which this search was not successful are considered below.

In figure 3 we show the averaged altitude (time) series (solid, irregular curve) of 32 cm band signal amplitudes in the upper region of enhanced scintillations of the Venus polar atmosphere. The ensemble averages were determined by using of three amplitude realizations obtained in the 24th, 28th and 30th sessions of radio occultations (October 23, 24 and 25, 1983). The model sine function (smooth curve shown superimposed) $0.3 sin(43t/180)$ was fitted to measured dependence, and it is represented for comparison. The cross-correlation coefficient for the experimental and model dependences is equal to $b_\chi \simeq 0.8$. The altitude

Table 1. The coefficients of cross-correlation of the amplitude fluctuations in the different sessions of radio measurements in the altitude interval 61.5–65.0 km.

N sessions	N24 (85.3N, 308.9W) 23.10.1983	N28 (87.0N, 301.2W) 24.10.1983	N30 (86.5N, 310.4W) 25.10.1983	N42 (85.5N, 179.7W) 31.10.1983
N24	–	0.69	0.60	0.60
N28	0.69	–	0.48	0.61
N30	0.60	0.48	–	0.37
N42	0.60	0.61	0.37	–

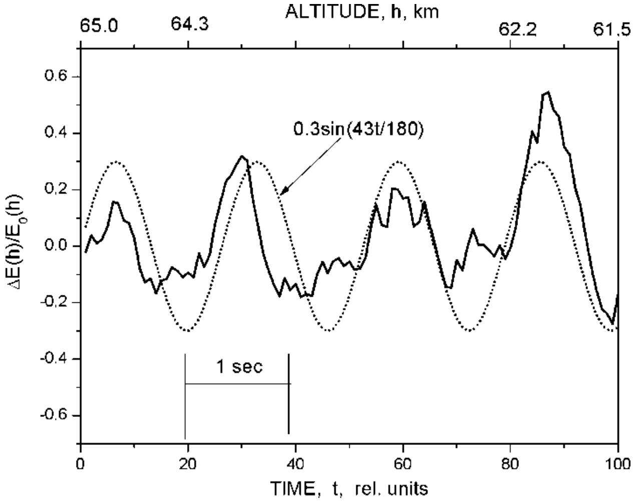

Figure 3. The averaged altitude (time) series (solid, irregular curve) of 32 cm band signal amplitudes in the upper region of enhanced scintillations of the Venus polar atmosphere. The ensemble averages were determined by using of three realizations obtained in the 24th, 28th and 30th sessions of radio occultation (October 23, 24 and 25, 1983).

scale size in the Venus atmosphere which is correspondent to the time period of the sine function is about 1 km.

Figure 4 shows the observed log-amplitude power spectra in the 24th, 28th and 30th radio occultation. The total variances σ^2 for each session are also represented. Let us consider the example for comparison: the *Pioneer Venus* radio occultation measurements at S-band (13 cm) in the same Venus region (latitude 86.6 N, 1978) show that $\sigma_{13}^2 = 0.044$. The layers were not discovered and the total variance σ_{13}^2 was associated with turbulence alone. Taking into account wavelength dependence $\sigma^2 \sim \lambda^{-7/6}$ which takes place for well-developed turbulence [3], the total variance in our case (if the layers are absent and $\lambda = 32$ cm) must be equal to $\sigma_{32}^2 \approx 0.018$. Indeed, the variances measured by us are much more than predicted measurements, which points to possible layering in the observed region.

The averaged log-amplitude power spectrum is shown in figure 5. The ensembles averages were determined by using three log-amplitude power spectra in the 24th, 28th and 30th sessions of radio occultations. In figure 5, the frequency of ~0.7 Hz correspondending to the altitude scale size ~1 km (the spatial period of the model sine function in figure 3) is shown by an arrow. If only turbulence takes place in the atmosphere, then $W_\chi(f)$ varies as $f^{(1-p)}$ at the high-frequency end [3]. In this case, p can be readily determined from the slope of the high-frequency asymptote of $W_\chi(f)$ when it is displayed on a log–log plot. The slope of -2.7 corresponds to the case of Kolmogorov turbulence ($p = 11/3$), but the slope of -4 corresponds to the saturated gravity wave spectrum ($p = 5$) [9]. Note that the slope of the high-frequency asymptote of the measured averaged spectrum is consistent with that of the saturated gravity wave spectrum.

For separation of the effects of regular (layers) and random (turbulence) parts from the observed amplitude scintillations, a simple model was used:

$$\chi = \chi_r + \delta\chi$$
$$\chi_{2r}(h, t + \tau) = A(\tau) \cdot \chi_{1r}(h, t)$$

Here χ_r and $\delta\chi$ are the regular and random parts of χ, correspondingly, τ is the time interval between the χ_1 and χ_2 measurements ($\tau > 0$), and $A(\tau)$ is an unknown evolution constant of

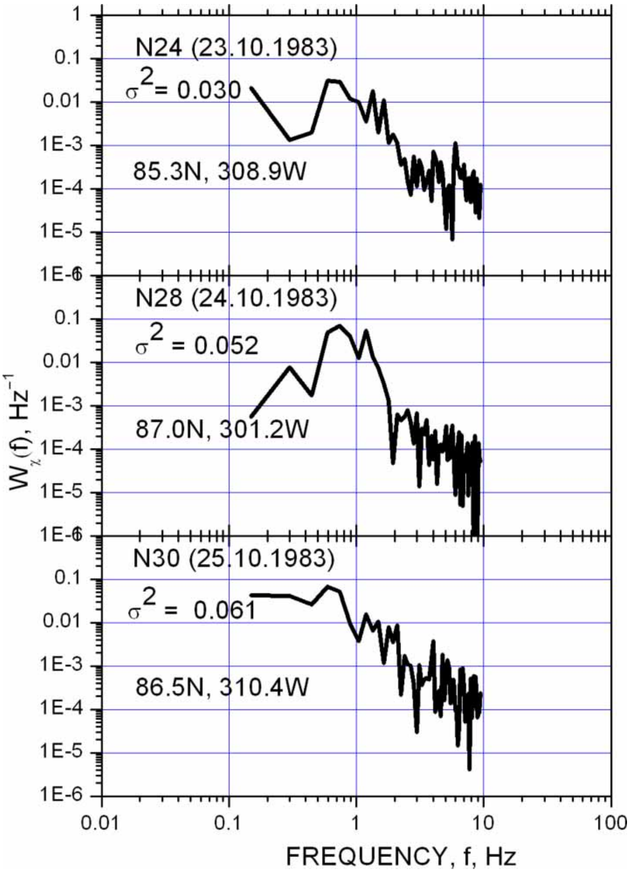

Figure 4. Observed log-amplitude power spectra in the 24th, 28th and 30th sessions of radio occultations. The total variances σ^2 for each sessions are represented ($\sigma^2 \ll 1$ – weak scintillation theory is applicable).

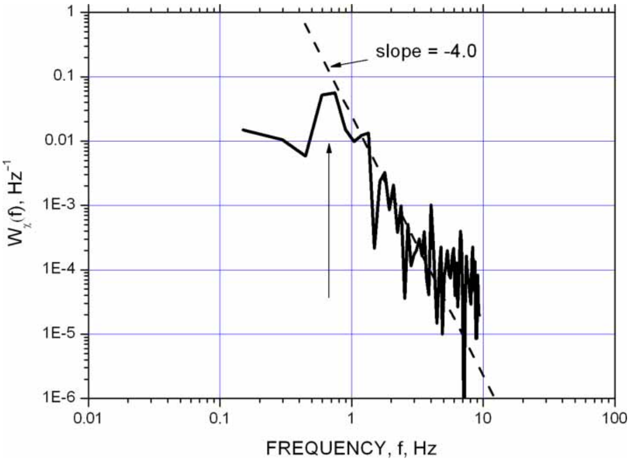

Figure 5. The averaged log-amplitude power spectrum. The ensemble averages were determined by using three log-amplitude power spectra obtained in the 24th, 28th and 30th sessions of radio occultations. A dotted line with the slope of −4.0 is depicted.

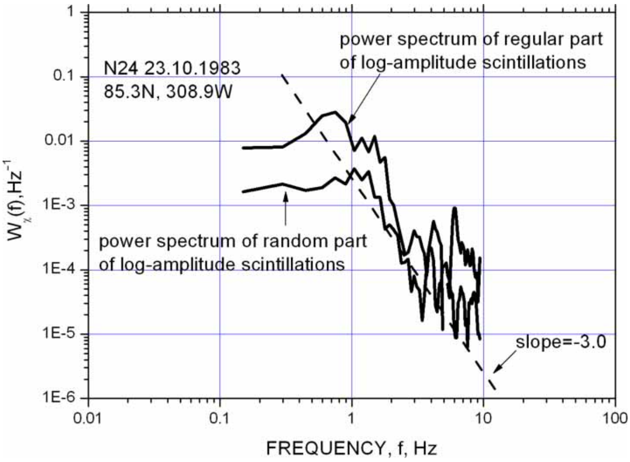

Figure 6. The power spectra of regular (layers) and random (turbulence) parts of log-amplitude scintillations for session N24.

the layered cluster; $A > 0$ (growth of the layer), $A < 0$ (decay of the layer). Assuming the same shape of the power spectra for turbulence in the adjacent examined regions and using this model for the cross-correlation analysis of the amplitude data we determined the regular and random parts of the total variances for the examined sessions.

Figure 6 shows the power spectra of regular and random parts of log-amplitude scintillations for session 24 (85.3 N, 308.9 W, 23.10.1983). The results of cross-correlation analysis of the data in sessions 24, 28 and 30 were used to obtain the spectra presented in figure 6. We see that the power spectrum of the random part of log-amplitude scintillations is fairly consistent with a slope of -3 (Kolmogorov turbulence). But the spectral amplitudes of regular parts of scintillations vary at the high-frequency end more steeply than the spectral random parts. As is seen from figure 6, the spectral amplitudes of the regular part are much greater than the spectral amplitudes of random parts, and the layers are dominant in session 24. Thus, we see that the small-scale structures in the amplitude–time record are caused by a combination of two scintillation sources. These sources are the permanent layers and turbulence.

3. Discussion of results and conclusions

Cross-correlation analysis of the amplitude fluctuations revealed in the different sessions points to the following facts.

1. Inner layering of the upper layer of the Venusian clouds is observed in the northern polar atmosphere. The vertical structure of the small-scale irregularities was identical in three regions at altitudes of 61.5–65.0 km sounded on October 23, 24, and 25, 1983.
2. The characteristic lifetime of the small-scale structures, during which they remain essentially unchanged and do not disintegrate under the effect of different unfavourable factors (atmosphere circulation, turbulence, etc.), exceeds the time interval between the measurements equal to 49 h.
3. In some cases (October 23, 24 and 25), the regular layers observed against the constant background of random turbulence in the upper cloud layer may be distinctly identified by their prevailing contribution (existence of the significant cross-correlation) to the formation of amplitude fluctuations in radio occultation measurements.

The conditions pointed out in 1 and 2 can be realized when a homogeneous layered structure covers along the horizontal both sounded regions, which are located almost along the meridian at a distance of about 130 km. In this case, the scale ~130 km (the estimate from below) specifies the horizontal dimensions of the layered structures in the northern polar Venusian atmosphere at altitudes of 61.5–65.0 km. The absence of vertical convection due to the isothermality of the polar atmosphere [7] and practically total suppression of the zonal winds at high latitudes ($\varphi \geq 84°$) at levels $h \geq 62$ km [10] are factors favourable for nondestruction of the layered structures.

Taking the above into account, let us note that if the existence of the cross-correlation of the amplitude fluctuations uniquely indicates the existence of the layered structures in the atmospheric regions that are sounded, then its absence does not prove the opposite, since experimentally determined values of the cross-correlation coefficient can be grossly underestimated due to the intense turbulent background in the atmosphere under study. The cross-correlation of the amplitude fluctuations also will not be detected if only one of the two sounded regions lies in the layered region of the atmosphere. Therefore, the detection of the cross-correlation of the amplitude fluctuations in the radio occultation measurements is a fairly rare event that can be observed under a favourable concurrence of circumstances in the course of the experiment. In our opinion, this is the cause of the absence of the cross-correlation of fluctuations in other pairs of the studied sessions.

We believe that the formation of the small-scale layered structures observed by the radio occultation data at altitudes of 61.5–65.0 km in the polar atmosphere may be associated with phase transitions in the aerosol medium of the upper layer of the Venusian clouds. In [11], the diagram of the phase state of the sulphuric acid–water system is represented, from which it follows that the temperature of the phase transition from the liquid to solid state for tetrahydrate $H_2SO_4 \cdot 4H_2O$ is very close to the temperature $T = 245–246$ K [7] that is characteristic of the isothermal atmosphere in the northern polar region at altitudes of 61–68 km. It is possible that it is precisely phase transitions which lead to the emergence of the observed layering, and that the heat released and absorbed in these phase transitions causes local heating and cooling in the atmosphere, which manifest themselves in the form of small inversions of temperature in the altitude dependencies [7].

Acknowledgements

This work was supported by the RFBR Grant 07-02-00738.

References

[1] R. Woo, A. Ishimaru and W.B. Kendall. J. Atmos. Sci. **31** 1698 (1974).
[2] R. Woo. J. Atmos. Sci. **32** 1084 (1975).
[3] R. Woo, J.W. Armstrong and A. Ishimaru. J. Geophys. Res. **85** 8031 (1980).
[4] T.S. Timofeeva, O.I. Yakovlev and A.I. Efimov. Kosm. Issled. **16** 285 (1978) (in Russian).
[5] M.Ya. Marov, B.V. Byvshev and B.P. Baranov *et al.*, Kosm. Issled. **21** 269 (1983) (in Russian).
[6] R. Knollenberg, L. Travis and M. Tomasko, *et al.*, J.Geophys. Res. **85** 8059 (1980).
[7] O.I. Yakovlev, S.S. Matyugov and V.N. Gubenko. *Icarus* **94** 493 (1991).
[8] A.S. Gurvich, A.I. Kon, V.I. Mironov, S.S. Khmelevtsov. *Lazernoe izluchenie v turbulentnoi atmosphere (Laser Radiation in the Turbulent Atmosphere)*. Nauka, Moscow: (1976) (in Russian).
[9] V. Kan, S.S.Matyugov and O.I. Yakovlev. *Radiofizika* **XLV** 652 (2002) (in Russian).
[10] I.R. Vaganov, O.I. Yakovlev, S.S. Matyugov and V.N. Gubenko. Kosm. Issled. **30** 695 (1992) (in Russian).
[11] L.V. Ksanfomaliti. *Planeta Venera (The Venus Planet)*. Nauka, Moscow (1985) (in Russian).