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# Detection of Ionospheric Layers in the Dayside Ionosphere of Venus at Altitudes of 80–120 km from Venera-15 and -16 Two-Frequency Radio-Occultation Results

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**Abstract**—We propose a technique for analyzing radio-occultation data that allows the effects of the noise, ionosphere, and atmosphere on the radio-occultation results to be reliably separated. This enables a more accurate investigation into the ionosphere formation mechanisms. Ionized layers are shown to exist in the dayside ionosphere of Venus at altitudes from 80 to 120 km. The position of the lower boundary of this ionized region can vary over the range of 80–100 km and the electron density gradients can change several times several.

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## 1. INTRODUCTION

The ionosphere of Venus was discovered in the radio-occultation experiment conducted in 1967 with Mariner 5. Systematic studies of the Venusian ionosphere were carried out from 1975 to 1994 with Venera 9 and 10 [Aleksandrov et al., 1978], Pioneer–Venus [Cravens et al., 1981; Venus, 1983], Venera 15 and 16 [Savich et al., 1986; Gavrik and Samoznaev, 1987], and Magellan [Jenkins et al., 1994]. The radio-occultation experiments yielded ~400 vertical profiles of the electron density under various solar illumination conditions, which allowed the main patterns of behavior of the Venusian ionosphere to be investigated. However, interest in investigating Venus has not decreased. In 2006, Venus–Express was placed in its orbit [Haeusler et al., 2006], which is still conducting radio-occultation experiments. Unfortunately, much of the data from foreign missions is inaccessible for a detailed analysis using our new data processing techniques.

The goal of this paper was to obtain new information about the ionosphere of Venus from Venera-15 and -16 two-frequency radio-occultation data. Progress in the radio-imaging theory and in the digital signal processing techniques made it possible to investigate the unknown layered structure of the Venusian ionosphere through the application of more sophisticated data processing methods. The high degree of coherence and stability of the radio signals at wavelengths of 32 and 8 cm from Venera 15 and 16 allowed a more accurate analysis of radiophysical parameters in the Venusian ionosphere to be performed. This was also facilitated by the fact that the refraction of the radio signal at 32 cm in the ionosphere exceeds that of the signal at 13 cm used in foreign research by a factor of 6.

## 2. THE TECHNIQUE OF MEASUREMENTS

Two-frequency radio-occultation observations of the ionosphere were performed from October 12, 1983, to September 24, 1984, when Venera 15 and 16 went behind the Venusian disk and emerged from behind it. The antenna of the Deep Space Communication Center (Evpatoria) received coherent radio signals at wavelengths of 8 (CM) and 32 (DM) cm; the standard equipment provided amplification, heterodyning, and filtering and, subsequently, the signals were fed through separate channels to the equipment of a dispersion interferometer [Aleksandrov et al., 1978]. It performed signal isolation by a calibration heterodyne method, narrow-band filtering using PLL-based tracking filters, and measurement of the reduced phase difference with recording on a recorder tape. A digital recording system was also introduced in the ground-based equipment [Savich et al., 1986]. Its principle of operation consisted in the following. The DM (1 kHz ± 50 Hz) and CM (4 kHz ± 100 Hz) signals from the bandpass filters of the dispersion interferometer were coded with a two-channel 8-bit analog-to-digital converter, which eliminated the relative time shifts of the two coherent signals. The sampling rate was set from a hydrogen standard and its value of ~550 Hz was chosen so as to eliminate the superposition effects that arise when narrow-band signals are sampled. The digital electromagnetic field strengths were written on a magnetic tape.

Previously, in 1984–1986, these records were used to measure the reduced signal phase differences and to determine the vertical profiles of the electron density $N(h)$. They allowed the main properties of the Venusian ionosphere at altitudes from 120 to 1000 km to be

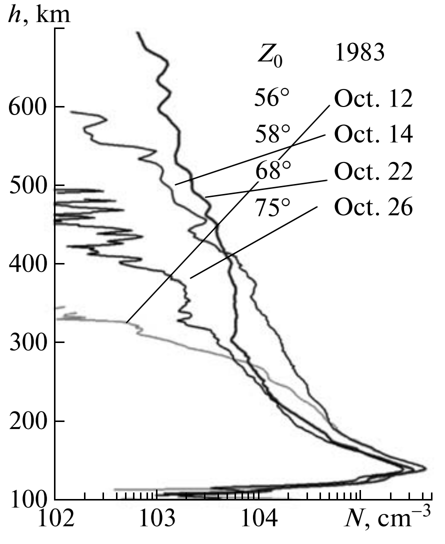

**Fig. 1.** Vertical profiles of the electron density $N(h)$.

investigated [Savich et al., 1986; Gavrik and Samoznaev, 1987]. As an example, Fig. 1 presents the $N(h)$ profiles for fourth zenith angles of the Sun $Z_0$.

Analysis of $N(h)$ showed that the ionopause—the boundary between the ionosphere and the solar plasma—is generally observed at 250–300 km at small $Z_0$ and at 600–1000 km at large $Z_0$, but its position can change by several hundred kilometers. The main ionization peak of the dayside ionosphere is located at altitudes of 138–148 km; at $Z_0 = 0°$, it has an electron density of $\sim 5 \times 10^5$ cm$^{-3}$ at minimum solar activity and $\sim 8 \times 10^5$ cm$^{-3}$ at maximum activity. Another ionization peak, an analogue of the $F2$ layer in the Earth's ionosphere, is formed at small $Z_0$ at altitudes of ~190 km. The lower ionization peak in the form of an inflection of the $N(h)$ profile is ~15 km below the main peak and has an electron density of $\sim 2 \times 10^5$ cm$^{-3}$ at $Z_0 = 0°$. As $Z_0$ increases, the electron density at the main and lower peaks decreases according to the law of a simple layer. A rapid decrease in $N(h)$ was observed below 130 km and it was assumed that there was no ionospheric plasma below ~115 km.

New software allowed highly accurate calculations of the amplitudes and phase increments of the DM and CM signals to be implemented with the maximum possible time resolution. This made it possible to apply a new technique for analyzing radio-occultation data that provided a reliable separation of the effects of the noise, ionosphere, and atmosphere on the radio-occultation results.

The signal phase increments allow the refraction angle $\xi(t)$ to be measured and the signal amplitudes allow the derivative of the refraction angle to be measured for radio waves propagating in the ionosphere and atmosphere in accordance with the following approximate relations:

$$\xi(t) \approx \frac{c}{V_\perp f}[\Delta f(t) + \Delta F(t)],$$

$$\frac{d}{dt}\xi(t) \approx \frac{V_\perp}{L}[X(t) - 1],$$

where $c$ is the speed of light, $L$ is the distance between the spacecraft and the pericenter of its line of sight, $V_\perp$ is the vertical component of the spacecraft ingress or egress velocity, $\Delta f$ is the change in the frequency of the signal (with the carrier frequency $f$) in the ionosphere, $\Delta F$ is the change in frequency in the upper atmosphere, and $X$ is the refractive attenuation of the signal power. In this approximation, the variations in refractive attenuation were shown to be directly proportional to the variations in the derivative of the change in signal frequency due to the influence of the medium being sounded:

$$X(t) = 1 + \frac{cL}{fV_\perp^2}\frac{d}{dt}[\Delta f(t) + \Delta F(t)].$$

To eliminate the effects of the atmosphere and spacecraft motion, we calculated the reduced frequency difference as a function of time $\Delta f$(t) [Savich et al., 1986]. $\Delta f(t) \approx \delta f(t)$ can then be assumed to be determined only by the plasma effect in the radio communication path.

Figure 2 presents the results of precise measurements with a time step of 0.06 s: $X(t)$ for the CM and DM signals and the variations in the derivative of $\Delta f(t)$, which are directly proportional to variations in the refractive attenuation of the DM signal, in accordance with the presented relation. The altitude of the line of sight of the spacecraft above the Venusian surface $h$ is along the vertical axis; the scale for $X(t)$ in relative units, where 1 corresponds to the absence of any effect of the ionosphere and atmosphere, is along the horizontal axis. We see from Fig. 2 that the effect of the ionosphere on the CM signal does not exceed the noise level, while the effect of the refractive attenuation in the atmosphere is observed below ~100 km. The effect of the ionosphere on the refractive attenuation of the DM signal exceeds significantly the measurement errors. Three distinct peaks of $X(t)$ attributable to the contraction of the line-of-sight tube when passing through ionized layers with steep gradients in refractive index are present at altitudes of 150–180 km. These peaks closely coincide with variations in the derivative of $\Delta f$(t) but do not correlate with variations in $X(t)$ for the CM signal, suggesting that the ionosphere has a layered structure in the altitude range of 150–180 km. A strong focusing of the DM radio beam due to a steep gradient in refractive index between the main and lower peaks of $N(h)$ is observed at 128 km. The next peak at 115 km is attributable to a rapid decrease in the electron density below the lower

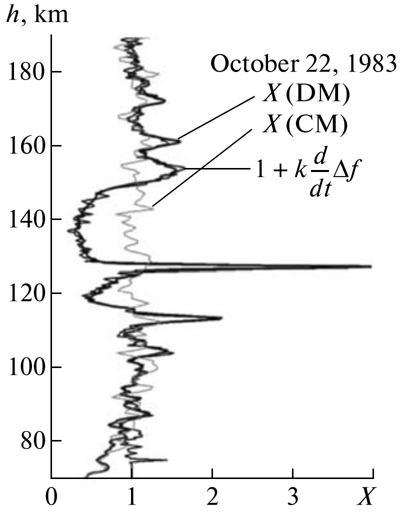

**Fig. 2.** Refractive attenuation $X$ for the DM and CM signals and variations in the derivative of $\Delta f$.

peak of $N(h)$. However, the most interesting peaks of $X(t)$ are those at 85, 88, and 105 km, which coincide with variations in the derivative of $\Delta f(t)$. This coincidence strongly suggests that ionized layers are present at altitudes of 80–120 km. The detected correlation between the variations in $X(t)$ and $\Delta f(t)$ cannot be a chance coincidence, since the noise fluctuations for the amplitude and frequency of the radio signal are different in nature and are completely uncorrelated. It should also be noted that the refractive attenuation below ~100 km is affected by both the ionized layers and the atmosphere, but the effect of the atmosphere is the same for $X(t)$ of the DM and CM signals and does not manifest itself in variations in the derivative of $\Delta f(t)$, while the effect of the ionized layers does not manifest itself in $X(t)$ of the CM signal and is the same for variations in the derivative of $\Delta f(t)$ and $X(t)$ of the DM signal.

Thus, the application of new techniques for analyzing the Venera-15 and -16 radio-occultation data revealed ionospheric plasma layers at altitudes of 80–110 km that were not observed in any of the missions to Venus.

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## REFERENCES

Yu. N. Aleksandrov et al., “Dayside Ionosphere of Venus According to the Data of Two-Frequency Radiosounding from the Venus-9 and Venus-10 Satellites,” Radiotekh. Elektron. **23** (9), 1840 (1978).

T. E. Cravens and A. J. Kliore, et al., “The Ionospheric Peak on the Venus Dayside,” J. Geophys. Res. **86A**, 11323 (1981).

A. L. Gavrik and L. N. Samoznaev, “Fetures of the Venus Dayside Ionosphere in the Years of Low and High Solar Activity,” Kosm. Issled. **25** (2), 285–291 (1987).

B. Haeusler, et al., “VeRa Experiment for Venus Express,” Planet. Space Sci. **54** (13–14), 1315–1335 (2006).

J. M. Jenkins, P. G. Steffes, et al., “Radio Occultation Studies of the Venus Atmosphere with the Magellan Spacecraft,” Icarus **110**, 79–94 (1994).

N. A. Savich et al., “Dayside Venus Ionosphere according to the Radio Occultation Data of the Venus-15 and -16 Satellites in 1983,” Radiotekh. Elektron. (Moscow) **31** (11), 2113 (1986).

*Venus*, Ed. by D. M. Hunten (Univ. Arizona Press, 1983).