Development of the sensitive technique for data processing during the satellites VENERA-15,-16 occultation experiments

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Abstract

New methods of data handling have been applied to reanalyze digital records obtained from VENERA-15,-16 dual-frequency occultation experiments. The regular existence of new ionospheric layers in the daytime Venus ionosphere at heights 80-120 km has been detected. The bottom border of this ionosphere part and gradients of the electron density show strong variability. We have detected the wave structure in the top atmosphere and in the bottom ionosphere at heights 60-115 km. To solve the inverse problem of radio probing and detection of the electron density we use a new technique developed to minimize errors.

1. Introduction

Between 1975 and 1994 regular researches of the Venus ionosphere were carried out by VENUS-9,-10 [1], PIONEER-VENUS [2,3], VENUS-15,-16 [4,5], MAGELLAN [6] and over 400 altitude distributions of electron densities were derived under various conditions of sunlight exposure. That data allowed getting the basic laws of the Venus ionosphere behavior. Nowadays occultation experiments are performed by a new satellite VENUS-EXPRESS [7]. The purpose of this article is to get new properties of the Venus daytime ionosphere reanalyzing VENUS-15,-16 dual-frequency occultation data. The high coherence and stability of radio signals of VENUS-15,-16 at wave lengths 32 cm (DM-signal) and 8 cm (CM-signal), along with the fact, that the DM-signal refraction in the ionosphere by factor 6 exceeds the signal refraction at 13 cm used by others researches [3,6,7], have allowed to perform analysis of radiophysical parameters in the Venus ionosphere more accurate. Progress in the radiovision theory and up-to-date digital processing techniques have provided an opportunity to discover unknown layered structure of the Venus daytime ionosphere.

2. Radio occultation experiment

VENUS-15,-16 dual-frequency occultation was carried out during Oct.12.1983 - Sept.24.1984. The Evpatoria ground station (Ukraine) received coherent radio signals and the regular equipment provided amplification and filtration of signals. After that signals were handled by the dispersive interferometer [1]. The closed-loop system of the dispersive interferometer performed narrow-band filtration and measurement of differential phase. Also the ground equipment included the digital registration system [4] with the following work principle: DM-signal (1 kHz ± 50 Hz) and CM-signal (4 kHz ± 100 Hz) received from narrowband filters were coded by dual-channel analog-digital converters with 8 bit. Digitization frequency ~550 Hz was formed by the hydrogen standard and the intensity of an electromagnetic field was written on magnetic tapes.

Earlier, in 1984-1986, these records were utilized to measure differential phase to get altitude distribution of the electron density *N(h)*. Any basic properties of the Venus daytime ionosphere at heights from 120 km up to 1000 km have investigated from that data [4,5]. Analysis of *N(h)* showed that ionopause is observed at heights 250-300 km under small zenith angle Z_O and at 600-1000 km under large Z_O, but its position can change within hundred kilometers. The main ionization maximum of the daytime ionosphere is situated at heights 138-148 km, under $Z_O=0^0$ it has electron density ~5 10^5 cm^{-3} during minimum sun activity and ~8 10^5 cm^{-3} during maximum sun activity. Under small Z_O at heights ~190 km one more ionization maximum is formed like the layer F2 of the terrestrial ionosphere. The bottom ionization maximum is about ~15 km below the main ionization maximum and it has electron density ~2 10^5 cm^{-3} under $Z_O=0^0$. With growth of Z_O the electron density in the main and bottom maxima decreases by the law of a simple layer. Below 130 km fast reduction of *N(h)* was observed and it was supposed, that below ~115 km there is no ionosphere plasmas.

The new software solution has performed high precision calculations of powers and phase increments of DM- and CM-signals with the greatest possible resolution on time interval $\Delta t=0.058$ *s*. The new technique of the occultation data analysis has provided reliable division of radiophysical effects into noise, ionospheres and atmospheres influences. The theoretical analysis has shown, that phase increments allow to measure the refractive angle $\xi(t)$, and signals powers allow to measure the time derivative of the refractive angle of the radio waves spreading in a thin ionosphere and in a thin top atmosphere, according to equations:

$$\xi(t) \approx \frac{c}{V_\perp f}\left[\Delta f(t)+\Delta F(t)\right], \qquad \frac{d}{dt}\xi(t) \approx \frac{V_\perp}{L}\left[X(t)-1\right],$$

where c – velocity of light, L – distance of satellite from a pericenter of the direct visibility line, $V_\perp$ – vertical velocity component of the satellite's ingress and egress, Δf – variations of the signal frequency in the ionosphere (assuming carrying frequency f), ΔF – variations of the signal frequency in the top atmosphere, X – refraction attenuation (X_{DM}, X_{CM} – for DM- and CM-signals). Along with that, it has been shown, that in the given approach variations of the refraction attenuation have to be proportional directly to variations of the signal frequency derivative if that variations was caused by influence of the medium:

$$X(t) \approx 1+\frac{cL}{f\,V_\perp^2}\frac{d}{dt}\left[\Delta f(t)+\Delta F(t)\right].$$

Hence the concordance of variations of X with variations of the refraction attenuation $X_{\Delta f}$ calculated on measurements of frequency will testify influence of the medium on radio signals. To exclude the influence of the atmosphere and satellite's movement the differential frequency was calculated as a function of time $\delta f(t)=16/15(f_{DM}-f_{CM}/4)$ [4]. It has been shown that $\Delta f(t) \approx \delta f(t)$ and $\delta f(t)$ depends only on plasma influence along the line of the radio ray. Then variations of $X_{\Delta f}$ depend only on ionosphere plasma influence.

3. Detection of layers in the ionosphere

Fig. 1 shows the measurement results with time discrete Δt=0.116 s and Δt=0.058 s. On Fig. 1a you can see that variations of X_{DM} (solid line) completely coincide with variations of $X_{\Delta f}$ (dotted line) at heights above 90 km and that testifies dominating influence of the ionosphere plasmas. Because of the atmosphere influence below 90 km the value of X_{DM} begins decreasing.

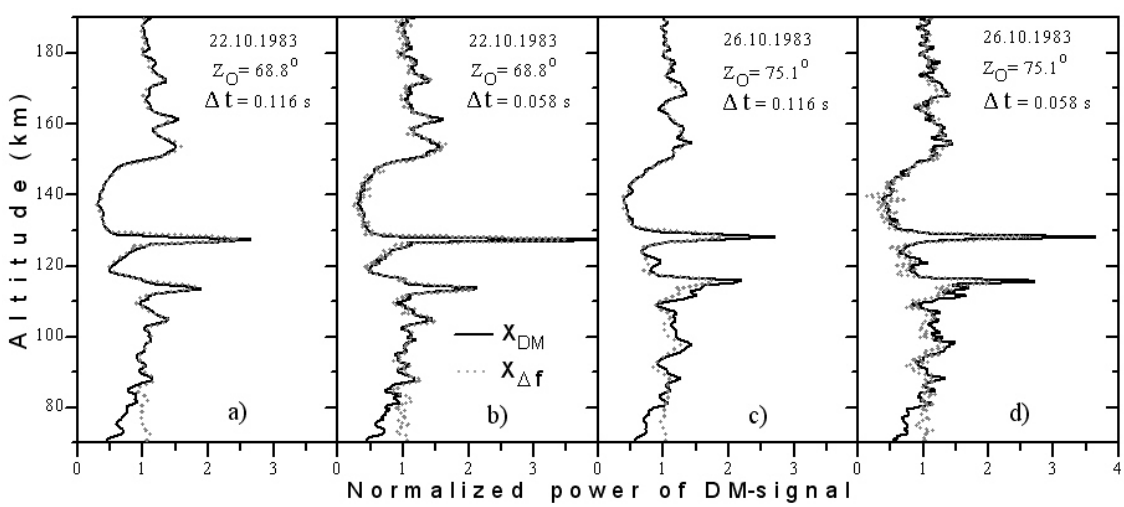

Fig. 1. Signatures of Dm-signal in the Venus daytime ionosphere.

Since a signal passed Fennel zones in ~0.33 s, it was expected, that Δt reduction by twice would not change variations of X_{DM}, and only increase its fluctuations. But the results presented on Fig. 1b show that reduction of Δt leads to more clear understanding about influence of the ionosphere on radio signals: strong focusing of a radio beam at height of ~130 km and increasing of DM-signal power by a factor 4 are observed. Fig. 1d shows the similar focusing of a radio beam. Such strong radio effect was not observed in earlier experiments. On Fig 1d it is easy to

see a mismatch between X_{DM} and $X_{\Delta f}$ in the refraction amplification maxima – the physical nature of such mismatches has not been investigated yet. Three maxima of X_{DM} on Fig. 1a,1b and two maxima of X_{DM} on Fig. 1c,1d at heights of 150-180 km show the layered structure of the ionosphere in this area. But the most important thing is a detection of the ionosphere layers at heights 80-120 km since earlier they were not observed and physical mechanisms of their formation are unknown. Existence of the bottom part of the ionosphere is proved by presence of maxima and minima of X_{DM} that coincide with variations of $X_{\Delta f}$ at heights from 110 up to 80 km (Fig. 1b) and at heights from 115 up to 90 km (Fig. 1d). The variations of $X_{\Delta f}$ are caused by not noise but ionized plasma since frequency and power measurements have different sources of errors and, hence, fluctuations of $X_{\Delta f}$ and X_{DM} as a noise can not be correlated.

On Fig. 2 comparison of results of measurements $X_{\Delta f}, X_{DM}, X_{CM}$ with Δt=0.058 s are presented. On Fig. 2a variations of X_{DM} (solid line) also completely coincide with variations of $X_{\Delta f}$ (dotted line) above 90 km. Below 90 km the refraction relaxation X_{DM} begins decreasing due to the atmosphere. The layered structure of the ionosphere appears at heights of 155-180 km. At heights of 90-115 km you can clearly see the influence of the bottom ionosphere plasmas. On Fig. 2b above 90 km variations of X_{DM} (solid line) do not correlate with variations of X_{CM} (thin solid line), since the ionized plasma influence is comparable to noise fluctuation of CM-signal due to the low signal/noise ratio. The influence of the ionized plasma on CM signal is less in 16 times than on DM signal. Below 90 km the refraction relaxation caused by the atmosphere is the same for both signals.

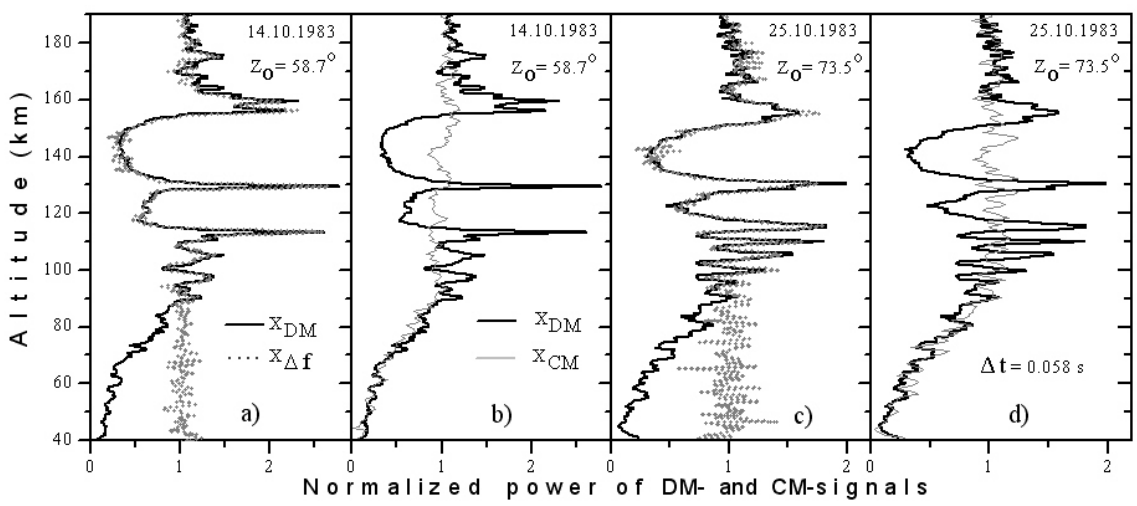

Fig. 2. Signatures of Dm- and SM-signals in the Venus daytime ionosphere.

The existence of the bottom layers in the Venus ionosphere was observed more brightly on Oct.25.1983. Coincidence of maxima and minima of X_{DM} and $X_{\Delta f}$ at heights of 85-115 km is precisely expressed on Fig. 2c. Probably, such structure of the bottom ionosphere layers is caused by the wave process proceeds in both the top atmosphere and the bottom ionosphere. Such assumption is testified by the fact that X_{DM} has recurrence of maxima and minima above 45 km (height of the direct visibility line of satellite without taking into account radio beam's bending). Event recurrence testifies a formation of layered structure in the top atmosphere during occultation experiment. Fig. 2d shows that recurrence of maxima and minima of X_{DM} (solid line) is matching with variations of X_{CM} (thin solid line) below 90 km. That is a notice of layered formations existence in the atmosphere in spite of the fact that noise of X_{CM} strongly distorts real variations of X_{CM} caused by the atmosphere. Analysis of the physical mechanisms of the formation of periodic layers structure will be performed later both for the top atmosphere and the bottom ionosphere.

The assumption of spherical symmetry of the ionosphere and application of Abel transformation allow to solve the inverse problem of occultation and evaluate *N(h)* [1,2]. But the technique used earlier [1,4] did not allow to determine real distributions of electron density below 115 km since errors of definition *N(h)* exceeded 3 10^3 cm^{-3}. The new, more accurate technique has been developed to reduce regular errors and calculate *N(h)* with accuracy better than 1%. The results of new method probing are shown in Fig 3. The error of *N(h)* measurement was found as follows. We constructed the electron density $N_0(h)$ with two layers in the top part ionosphere. The dependence $\delta f(t)$

was calculated for a certain orbit of the spacecraft and small frequency noise was added. Then the altitude profile $N_1(h)$ (solid line on Fig. 3a) was calculated from dependence $\delta f(t)$. The difference $N_1(h) - N_0(h)$ characterizes absolute error of $N(h)$ measurement (solid line on Fig. 3b), it is small and relative errors are less than 1% (solid line on Fig. 3c). If we add frequency trend (solar wind influence) to $\delta f(t)$ with value ±0.0004 Hz/s relative errors will be grater than 100% in the region h<120 km (thin and dot lines on Fig. 3b,3c). Therefore it is difficult to obtain true electron number density $N(h)$ in the region h<120 km, where we have detected new ionospheric layers. A new technique to minimize errors in the region h<120 km will be performed later.

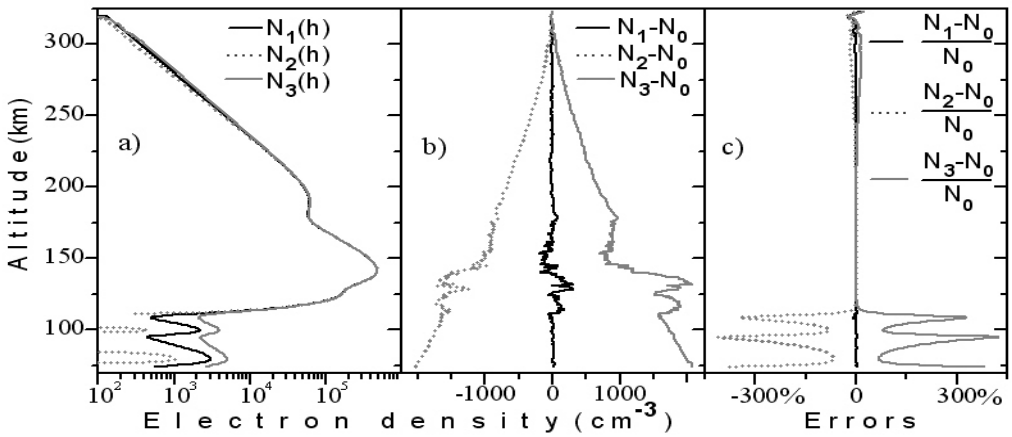

Fig. 3. Electron density profiles and errors obtained by solving the inverse problem.

4. Conclusion

1. The results of new data analysis have shown the regular existence of the ionospheric layers in the daytime Venus ionosphere at heights from 80 up to 120 km.
2. The wave structure has been detected in the top atmosphere and in the bottom ionosphere at heights 60 - 115 km.
3. It has been shown that the 32 cm signal power can be amplified by a factor 4 in the main maximum region of the Venus daytime ionosphere.
4. It has been shown that the main maximum region of the daytime ionosphere at heights of 150-190 km has a layered structure with significant gradient variations in electron density.

5. Acknowledgments

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6. References

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