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Abstract

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RADAR OBSERVATIONS OF VENUS IN THE SOVIET UNION IN 1964

The Institute of Radio Engineering and Electronics of the Academy of Sciences of the USSR, jointly with a number of organizations, continued radar observations of Venus during the period from 11 to 30 VI 1964. The measurements were carried out at a wavelength of about 40 cm on the same installation as in 1961 ([1]) and 1962 ([2]). Paramagnetic and parametric amplifiers were used at the receiver input. Signal analysis was performed from magnetic tape by a 20-channel analyzer; the bandwidth of the filters of each channel, recalculated to the received signal, was 1.2 Hz.

For the investigation, two types of modulation of the transmitted signal were used mainly: frequency keying and periodic linear frequency modulation, analogous to what was done in 1962 ([2,3]).

With frequency keying, the transmitted signal had the form of alternating telegraph pulses at two frequencies, which differed either by 62.5 Hz or by 2000 Hz. The duration of the pulses and pauses at each frequency was 4.096 sec. This type of modulation was used to study the spectrum of the reflected signals and to measure the radial velocity of the motion of Venus, which was determined from the Doppler shift of the central frequency of the signal spectrum relative to the transmitted frequency.

Linear frequency modulation was used to study the law of reflection of radio waves from the surface and to measure the distance to Venus. The frequency of the transmitted oscillations was periodically varied according to a sawtooth law ([3]); in this case three modes were used: a deviation of 4 kHz with a period of 1.024 sec (as in 1962), a deviation of 32 kHz with a period of 8.192 sec, and a deviation of 32 kHz with a period of 1.024 sec. Increasing the deviation by a factor of 8 made it possible to increase by the same factor the accuracy of the distance measurement and the resolving power for studying the law of signal reflection from the surface. During reception, the heterodyne frequency was also varied according to a sawtooth law, but with a delay equal to the calculated propagation time of the signal to the planet and back. If the calculated delay corresponded exactly to the actual propagation time of the signal to the planet

Fig. 1. Change in the distance to Venus (a) and in the radial velocity of its motion (b) relative to the calculated value, June 1964.

Figure 1: Fig. 1. Change in the distance to Venus (a) and in the radial velocity of its motion (b) relative to the calculated value, June 1964.

Fig. 2. Distribution, by range, of the energy of signals reflected from Venus. a —obtained with linear frequency modulation with a deviation of 4 kHz ($\sigma = 0.0025$ for narrow filters and $\sigma = 0.0014$ for wide filters); b—obtained with a deviation of 32 kHz.

Figure 2: Fig. 2. Distribution, by range, of the energy of signals reflected from Venus. a—obtained with linear frequency modulation with a deviation of 4 kHz ($\sigma = 0.0025$ for narrow filters and $\sigma = 0.0014$ for wide filters); b—obtained with a deviation of 32 kHz.

and back, then the signal frequency at the receiver output was nominal. From the deviation of the signal frequency from the nominal value, a correction to the calculated delay time was found.

The results of measurements of the distance to Venus and of the radial velocity of its motion are presented in Fig. 1. In Fig. 1*a* is plotted the difference Δr (km) between the measured and computed value of the distance from the measuring station to the nearest point of the surface of Venus; in Fig. 1*b*, the difference Δv_r (cm/sec) between the measured and computed value of the radial velocity of the center of reflection on Venus relative to the measuring station. The vertical segments show the root-mean-square errors of the measured values.

When measuring the distance, the rms value of the instrumental error over one 5-minute session did not exceed 15 km before June 23 (at a deviation of 4 kHz) and 2 km after June 23 (at a deviation of 32 kHz); the error in measuring the velocity did not exceed 2.5 cm/sec.

Fig. 1. Change in the distance to Venus (*a*) and in the radial velocity of its motion (*b*) relative to the calculated value, June 1964.

In the calculations of the signal propagation time and of the Doppler frequency shift, the following were adopted: astronomical unit 149,598,000 km, speed of light 299,792.5 km/sec, radius of Venus 6100 km. The signal propagation time was calculated with an accuracy of ±5 μsec, and the Doppler frequency to ±0.05 Hz. The computation of the coordinates of the planets was performed on the basis of Newcomb' s analytical theory, taking into account corrections to the orbital

Fig. 2. Distribution, by range, of the energy of signals reflected from Venus. *a*—obtained with linear frequency modulation with a deviation of 4 kHz ($\sigma = 0.0025$ for narrow filters and $\sigma = 0.0014$ for wide filters); *b*—obtained with a deviation of 32 kHz.

Fig. 3. Dependence of the energy of reflected signals P on the angle of incidence φ.

Figure 3: Fig. 3. Dependence of the energy of reflected signals P on the angle of incidence φ.

elements of Venus according to Duncombe’ s data and corrections to the orbital elements of the system.

Earth—Moon according to Morgan’ s data. In addition, the calculations took into account an additional displacement of the center of Venus along its orbit in the direction of motion by 250 km. The displacement was determined in 1962 [2] and was estimated at 270 km, which is equivalent to increasing the heliocentric longitude of Venus by $+0''.52$. This displacement in Figs. 1a and 1b corresponds to the smooth curves 1. If the introduced correction for the displacement did not in fact exist, then the experimental points would have to lie on the smooth curves 2. The dashed lines in Fig. 1a show how the value Δr should change if the actual value of the astronomical unit were equal to 149,598,100 and 149,597,900 km. The value of the astronomical unit from these measurements is 149,598,000 km; moreover, if possible systematic errors are taken into account, the maximum error may be ±400 km.

Fig. 3. Dependence of the energy of reflected signals P on the angle of incidence φ.

The root-mean-square values of the systematic errors of the initial data, when converted to the astronomical unit, are estimated by the following values: speed of light, 70 km; radius of Venus, 40 km; heliocentric coordinates of Venus and Earth, 100 km; influence of the medium in which the signal propagates, 10 km; other constants (Earth’ s radius, ratio of the masses of the Moon and Earth, etc.), 10 km; determination of the delay in the apparatus, 5 km. The total root-mean-square error is 130 km.

The distribution of the energy of signals reflected from Venus as a function of the distance ΔR relative to the portion of its surface nearest to Earth is shown in Fig. 2. The distribution in Fig. 2a was obtained from 27 sessions with linear frequency modulation at a deviation of 4 kHz and a period of 1.024 sec. The first 11 columns represent the energy of signals reflected by annular zones of the surface with depths up to 45 km; the remaining ones, up to 150 km. The distribution in Fig. 2b was obtained from 20 sessions at a deviation of 32 kHz with a period of 1.024 sec, the use of which made it possible to study in more detail the law of reflection for the forward portion of the surface and to obtain the energy from annular zones with depths up to 5.5 km. From these data the dependence of the energy of the reflected signals P on the angle of incidence φ was found (Fig. 3, curve 1). For comparison, in the same figure, curve 2 shows the analogous dependence obtained from the 1962 measurements.

A comparison of the results shows that in 1964 the energy of the reflected signals

Fig. 4. Determination of the rotation period of Venus from the results of radar observations in 1962 (a) and 1964 (b). Ω is the angular velocity of rotation of Venus relative to the locator. The dashed lines indicate calculated values of Ω for direct rotation of Venus; the solid lines, for retrograde rotation.

Figure 4: Fig. 4. Determination of the rotation period of Venus from the results of radar observations in 1962 (a) and 1964 (b). Ω is the angular velocity of rotation of Venus relative to the locator. The dashed lines indicate calculated values of Ω for direct rotation of Venus; the solid lines, for retrograde rotation.

decreases with increasing angle φ more rapidly than was observed in 1962. This can apparently be explained by the fact that, during the 1964 radar observations, Venus was turned toward Earth by its smoother side.

The width of the Doppler spectrum of the reflected signal, caused by the rotation of Venus, does not exceed 15 Hz. The reflection coefficient [3] of Venus, measured from the total energy of the received signal, is on average 19%. The energy in the central band of 1 Hz is approximately 2 times less than the energy of the entire spectrum.

The spectra of individual days of observation were used to determine the rotation period of Venus. For this purpose they were compared with a calculated spectrum computed for different rotation periods from the law of distribu-

of energy shown in Fig. 2. The results obtained in 1964 do not contradict the conclusion of retrograde rotation of Venus with a period of 200–300 days, drawn from the radar observations of Venus in 1962. (2) Figure 4 shows the experimental results of 1962 (3) (a) and 1964 (b). All these results agree well with one another and correspond best to retrograde rotation of Venus with a period of 230 days $±$25 days.

Joint consideration of the results of determining the rotation period in 1962 and 1964 shows that the orientation of Venus' s rotation axis is close to perpendicular to the plane of its orbit.

Fig. 4. Determination of the rotation period of Venus from the results of radar observations in 1962 (a) and 1964 (b). Ω is the angular velocity of rotation of Venus relative to the locator. The dashed lines indicate calculated values of Ω for direct rotation of Venus; the solid lines, for retrograde rotation.

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