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Abstract

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RADAR OBSERVATION OF VENUS

As was indicated in preliminary communications ([1,2]), in April 1961 the Institute of Radio Engineering and Electronics of the Academy of Sciences of the USSR, together with a number of organizations, carried out radar observations of the planet Venus. The frequency of the space-radar transmitter was about 700 MHz. The power-flux density was 250 MW per steradian, which gave 15 W at the surface of Venus. The polarization of the transmitted waves was circular. On reception the antenna had linear polarization. The transmitted signal consisted of rectangular pulses of duration 128 or 64 msec, separated by pauses of the same length. On some days, instead of pauses, a pulse of the same duration but at another frequency was given. Calculated corrections for the Doppler shift caused by the change in distance between the Earth and Venus and by the rotation of the Earth were introduced into the frequency of the signal and of the modulation on transmission. The frequencies of the transmitter, of its modulation, and of the receiver heterodynes were set by a precision quartz generator with stability better than 10^{-9}.

Transmission was carried out in sessions during the time required for the signal to travel from the Earth to Venus and back (about 5 min). Reception was then carried out for the same length of time.

The incoming signals were received by a superheterodyne receiver, at whose output the signal reflected from Venus was to have a frequency of about 700-750 Hz (depending on the value of the astronomical unit). This signal, together with the noise, was recorded on magnetic tape in the band 420–1020 Hz. On the same tape was recorded an oscillation with frequency 2000 Hz, serving as a time scale and used to monitor and maintain the speed of motion of the magnetic tape during playback. The beginning of the recording of this oscillation corresponded exactly to the calculated moment of arrival of the 5-minute series of reflected signals, which made it possible to judge how much the actual time of propagation of the signal to Venus and back differed from the calculated one.

The oscillations from the magnetic tape were analyzed by means of wide-band and narrow-band analyzers. The wide-band analyzer contained 10 filters with passbands of 60 Hz, covering the frequency range from 420 to 1020 Hz. After each filter the difference energy was determined,

Fig. 1

Figure 1: Fig. 1

Fig. 2

Figure 2: Fig. 2

$$\Delta W_\tau = W' - W'', \tag{1}$$

where W' is the total energy of the oscillation at the filter output over time intervals shaded once (see Fig. 1), and W'' is the analogous energy over intervals shaded twice.

The accumulation of energy was carried out by means of counters of discrete pulses, the number of which was proportional to the energy. The narrow-band analyzer contained 10 filters with a band of 4 Hz each, covering a band of 40 Hz. In this case, switching of the signal in accordance with Fig. 1 was carried out not at the output of the filters, as was done in the wide-band analyzer, but at their input.

Analysis of the spectrum of the reflected signals showed that they can be represented as the sum of two components—a narrow-band and a wide-band one. The width of the narrow-band component was determined mainly by the amplitude modulation of the transmitted signals and did not exceed a few hertz. The width of the wide-band component was several hundred hertz. Examples of the spectra of these components, obtained over 5 sessions on 18 IV 1961, are shown in Fig. 2. In order that the narrow-band component should not distort the spectrum of the wide-band one, a notch filter was placed before the wide-band analyzer. In Fig. 2 the horizontal dashed lines show the value of the root-mean-square error of measurement.

Fig. 1. t_0—calculated time of arrival of a series of reflected signals (the instant when the recording of the 2000-Hz oscillation begins); T—modulation period; τ—delay set as desired; 1—power of the sum of the reflected signal and noise; 2—the actually arrived reflected signal; 3—2000-Hz oscillation

Figure 3 shows the average total power separately for the narrow-band and wide-band components on different days. The spectral density of the energy of the narrow-band component was two orders of magnitude greater than that of the wide-band component.

Comparing the energy of the narrow-band component with the energy that the receiver picked up from a discrete source—the radio star A Cassiopeiae—it was established that this component contained 8% of the energy that would have been received if Venus were a smooth, well-conducting sphere.

Fig. 3

Figure 3: Fig. 3

Fig. 2. Spectra of reflected signals over 5 sessions on 18 IV 1961: narrow-band (a) and wide-band (b) components. Ordinate—the ratio of the mean signal power after the filter to the noise in a 1-Hz band; abscissa—the filter frequency

The magnitude of the astronomical unit of length (the mean distance between the Sun and the center of gravity of the Earth–Moon system) was determined in two ways: from the Doppler shift of the spectrum of the narrow-band component and from the delay of the reflected signal, since this gave the distance between Venus and Earth and the rate of its change in meters, while from calculation these same quantities were known in astronomical units. In Fig. 2a a scale is given showing the calculated value of the middle of the spectrum of the reflected signal as a function of the magnitude of the astronomical unit. As can be seen, the spectrum in Fig. 2a corresponded to an astronomical unit of $149.6 \cdot 10^6$ km. Averaging the values obtained by this method over all days of observation gave a value of the astronomical unit of 149 598 000 km (with a root-mean-square error of 3300 km).

The values of the astronomical unit obtained from the delay of the narrow-

narrowband component of the reflected signal for individual sessions, are shown in Fig. 4. The mean of these values gives the value 149,599,300 with a root-mean-square error of 570 km. In this calculation the following possible errors were taken into account: from the scatter of individual measurements, 330 km; from lack of knowledge of the exact radius of Venus (the error in its value was taken to be 70 km), 220 km; from lack of knowledge of the exact value of the speed of light, 100 km; from a systematic unaccounted delay in the apparatus, 340 km; from an inaccurate calculation of the Earth—Venus distance in astronomical units, 220 km. In the calculation the radius of Venus was taken as 6100 km and the speed of light as 299,792.5 km/sec.

Fig. 3. Total mean power of the components of the reflected signal by day: of the narrowband component at $\tau = 0$ (1) and of the broadband component at $\tau = 16$ msec (2). The ordinate is the ratio of the mean signal power to the noise in a 1-Hz band.

Because of the periodicity of the signal used, its delay time and the astronomical unit were determined by this method ambiguously. Thus, the astronomical unit came out equal to $149\,599\,300 \pm Ln$, where n is an integer, and L, for pulses with a period of 256 msec, is equal to $120\,000 \div 130\,000$ km, depending on the day of observation. The ambiguity was resolved by two methods: by comparison with the value

Fig. 4. Values of the astronomical unit obtained from the signal delay in individual 5-minute sessions.

Fig. 4

Figure 4: Fig. 4

of the astronomical unit obtained by us from the Doppler shift of the spectrum, and by the constancy of the obtained value of the astronomical unit for different days. If the ambiguity had been resolved incorrectly, then the value of the astronomical unit over the time from 18 IV 1961 to 26 IV 1961 would have changed by ±11 000 km or more, which, in reality, as is clear from Fig. 4, did not occur*.

There is no doubt that the presence of the narrowband component of the signal can be explained only by reflection of the transmitted signals from the surface of Venus, since this component was observed regularly over many dozens of sessions and throughout had a delay and a Doppler frequency shift consistent with the motion of Venus. The obtained–

* The published preliminary data (1) contain an incorrect value of the astronomical unit, since the ambiguity at that time was resolved by comparison with the previously published values of the astronomical unit, determined by various methods. These values, obviously, were incorrect. Analysis with a narrowband analyzer had not yet been carried out at that time.

the parameters we obtained for the narrow-band component agree with the parameters of radar signals reflected from Venus that were observed in 1961 by other investigators (3-5).

The wide-band component was not observed by other investigators. The probability that random realizations of noise and interference were mistaken for the wide-band component was estimated–it proved to be of the order of 10^{-2}, or even less. A check of the transmitting and receiving apparatus showed that there was no spectral smearing of the signals in it that could explain the appearance of this component. Since the receiver was switched on approximately half a minute after the transmitter was switched off, no reflections of signals from formations close to the Earth (for example, the ionosphere) could have been received. The appearance of this component due to reflection from any "clouds" in outer space is also unlikely. For this, the velocity of their motion would have had to be close to the velocity of Venus; otherwise, because of the Doppler frequency shift, they would not have fallen within the receiver band. In addition, the delay of this component and of its individual parts, which passed through different filters of the analyzer, show that they came from a distance consistent with the distance to Venus. Thus, it is most likely that this component is also due, in its origin, either to reflection from the surface of Venus or to reflection from some formations near it.

Let us consider two possible variants.

A. The wide-band component is formed as a result of reflection of the signal from the entire surface of Venus and of the Doppler shift caused by its rotation. The narrow-band component is caused by reflection from the portion of the surface of Venus closest to us (the specular point).

Since the broadening of the spectral lines in the narrow-band component of the signal is at least 100 times smaller than in the wide-band component, one must assume that the "specular point" has a size less than 1/100 of the diameter of Venus. This may be the case if the surface of Venus is considerably smoother than the surface of the Moon.

Under this assumption, for a line broadening of ±200 Hz, the period of rotation of Venus should be about 10 days if its axis of rotation is perpendicular to the direction toward the Earth and the whole surface reflects. If the axis of rotation makes 60° with the direction toward the Earth (6), then the period is shortened to 9 days. If we did not register the whole spectrum and it is in fact wider than 400 Hz, then the period of rotation should be still smaller.

B. The reflecting properties of Venus are approximately the same as those of the Moon. Then the narrow-band component of the reflected signal should correspond, by analogy with the Moon, to reflection from a spot of 1/10 of the radius of Venus. In this case, taking into account that this component, according to our data, is narrower than 4 Hz, we obtain a rotation period greater than 100 days.

In this variant, the wide-band component cannot be explained by reflection from the surface of the planet, and one must suppose that it arose as a result of reflection from some formations moving with velocities up to ±40 m/sec relative to Venus, or even faster, for example from strongly ionized streams. However, for this the ionization in these streams must be much greater than in the Earth' s ionosphere. Recent data (7) indicate that this may be the case.

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Note: Figure translations are in progress. See original paper for figures.

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