

RADAR LOCATION ASTRONOMY

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Abstract. A review of the work on planetary radar performed at the Institute of Radioengineering and Electronics of the USSR Academy of Sciences from the 1960s to the early 1980s of 20th century is presented. The works were stimulated by the practical cosmonautics requirements that arose after 1957 and required a more accurate knowledge of the distances and motions of the planets of the solar system than what the optical telescopes developed in classical observational astronomy provided. Along with the refinement of the basis of all calculations - the astronomical unit and the construction of the theory of the motion of inner planets certain basic parameters of these planets and their orbits-the radius and nature of the rotation of Venus, its surface, and also the surfaces of Mercury and Mars, were refined. The size and composition of the particles of Saturn's rings are also studied. The work was carried out with the help of the planetary radar designed for them, and the methods and ground-based echo-signals processing software.

Keywords: astronomy, radar, echo-signals, astronomical unit, theory of motion of inner planets, characteristics of planets, planetary radar

UDC 621.396.967

Bibliography - 12 references

Received May 25, 1981[1]

RENSIT, 2018, 10(2):147-166

DOI: 10.17725/rensit.2018.10.147

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INTRODUCTION

In the last two decades, a new direction of observational astronomy has successfully developed, using physical principles and methods of radiolocation to study the celestial bodies of the Solar system: their positions, movements, rotation, sizes, physical properties of the constituent rocks, relief and other characteristics of the surface.

The rapid development of radar astronomy was stimulated and supported by the practical needs of astronautics, since for the flights of

space stations to planets more precise information was needed on the position and motion of the planets. Observations of the planets and the Sun, conducted over two centuries with the help of optical telescopes, made it possible to construct very perfect theories of their motion, however, the accuracy of calculating the position of the planets on their basis still did not satisfy the high requirements of astronautics.

Knowledge of the sizes of planetary orbits, expressed in kilometers, turned out to be especially insufficient, since direct measurements of distances to the planets are inaccessible to the optical means of classical observational astronomy. Indirect methods, based on measurements of the difference in the angular positions of the planets in the celestial sphere from different points of the Earth, led to large errors - hundreds of thousands of kilometers.

Unlike indirect optical methods, radar allows you to determine the distance to the planet directly from direct measurements of the time interval during which radio waves propagate to the planet and after reflection from it back to the radar. The speed of propagation of radio waves, equal to the

speed of light, is known with high accuracy, and therefore the accuracy of measuring the distance is also high. In addition, radiolocation makes it possible directly and with high accuracy along the Doppler shift of the frequency of reflected radio waves to determine the rate of change in the distance to the planet (radial velocity).

In modern planetary radars, the distance to the nearest sections of the planets is measured to accuracy a few hundred meters, the speed is until several centimeters per second. For example, our planetary radar (wavelength 39 cm), located in the Crimea, allows you to measure the distance to Venus to accuracy 300 m and the speed of planet - up to 0.8 cm/s. At the same time, it is possible to separate and measure the radio signals reflected from the individual parts of the planet being studied, since these signals come with different delay and have different Doppler frequency shifts caused by the rotation of the planet.

The radiolocation of the Moon was carried out in the first years after the Second World War; the radars created by that time had sufficient power for this. However, due to the fact that the power of the reflected radio waves returning to the locator decreases proportionally to the fourth power of the distance to the object to be detected, it was necessary to raise the radar power tens of millions of times or to increase the antenna size and sensitivity of the receivers in order to successfully locate the planets.

The first successful radiolocation of the planet was Venus - in the USSR, the USA and England it was carried out in April 1961, when it was at the minimum distance from the Earth (40 million km). In 1962, the radiolocation of Venus was repeated in the USSR, Britain and the USA, and in 1964 - in the USSR and the United States.

In the observations of 1962, the sensitivity of the radar of the USSR was increased sixfold - at that time it was the most sensitive (the sensitivity of the radar depends on the radiated power, the dimensions of the antenna, and the sensitivity of the receiver). The increase in sensitivity made it possible to measure the distance to Venus for two months and to reduce their errors by a factor of

70 compared with 1961. The distance in 1962 was determined with an accuracy of 12-15 km, speed - 6 cm/s.

For the first time, the energy distribution of the echo signal was obtained from the delay time with high resolution (**Fig. 1**), which allowed to draw conclusions about the nature of the reflecting surface of Venus. At the same time, for the first time (in the USSR and the USA), the direction and period of rotation of Venus was determined. The main result of observations of Venus in 1961, 1962 and 1964. was a cardinal (almost 1000 times) refinement of the astronomical unit - the average distance from the Earth to the Sun. In addition to great scientific value, this fundamental result was of utmost practical importance for the solution of navigational problems during flights of interplanetary.

The increase in the sensitivity of the radar of the USSR made it possible in June 1962 for the first time to conduct a successful radiolocation of Mercury. The first experiments on the radiolocation of Mars and Jupiter were conducted in 1963 in the USSR and the USA.

In January-February 1966, joint Soviet-British radar observations of Venus were carried out, in which radio waves toward the planet were emitted from the Center for Remote Space Communications

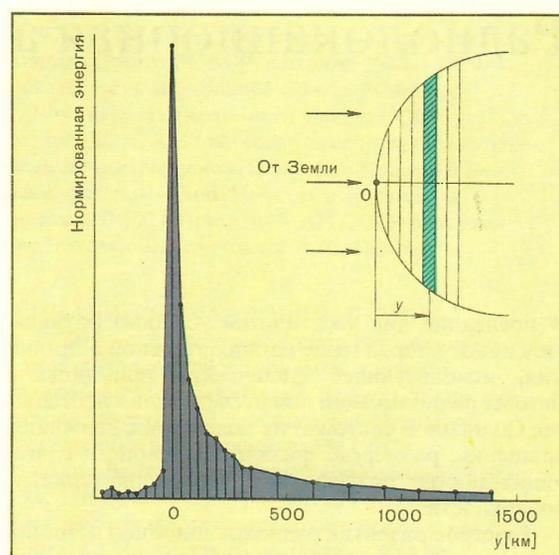


Fig. 1. The energy distribution of radio waves, reflected from Venus in terms of range (delay) (USSR, 1962). A sharp maximum at point 0 (the closest point of the planet to the Earth) says about mirror reflection in the center of the disk of the planet.

in the Crimea, and signals reflected from the planet were received and recorded on a magnetic tape at the Jodrell Bank [2]. Their processing was carried out independently in the USSR and England. The analysis of the obtained frequency spectra of echo signals made it possible to specify the period of rotation of Venus and to supplement information on the reflecting properties of its surface.

Since 1969, the planetary radar of the USSR performed regular measurements of the distance and radial velocity of Venus in order to predict the position of the planet at the final stage of flights to it of interplanetary stations. In the process of preparing for observations, the equipment and methods of observations were continuously improved in order to improve the accuracy of measurements.

Thanks to the increase in the transmitter power, the improvement of the antenna and the receiver, and also the improvement of the methods for processing echoes using computers, the radar sensitivity in the USSR was increased 70 times by 1971. This allowed during the great confrontation of Mars¹ 1971 (the minimum distance to Earth - about 56 million km) during two months to measure its distance from the Earth, which was necessary to ensure flights toward it of the interplanetary stations "Mars-2" and "Mars" -3".

In 1979, a full-rotating parabolic antenna with a mirror diameter of 70 m (**Fig. 2**) was constructed at the Center for Far-Eastern Space Communications in the Crimea, on the basis of which a more perfect planetary radar was created (at the same wavelength). The use of a high-efficiency antenna, increasing the transmitter power and improving the sensitivity of the receiver made it possible to increase the sensitivity of the USSR radar by a factor of 50, which increased the utmost radar range of the planets by more than 2.5 times.

With the help of this radar in the period from February to April 1980, radar observations of

¹In oppositions, Mars is visible in the sky in the constellations opposite to the Sun ("standing against the Sun"). In this case, the distance between Mars and the Earth is minimal, unlike the other positions of these planets in orbits.



Fig. 2. The receiving and transmitting full-rotating antenna with a diameter of 70 m of the Center for Remote Space Communications in the Crimea, used for the USSR's planetary radar since 1980.

Venus, Mars and Mercury were made on significant sections of their orbits, with the largest distances being 161 million km - to Venus, 135 million km to Mars, 139 million km - up to Mercury (these distances are not limit for locator). A new high-precision astrometric information has been obtained for three planets, which, together with the results of observations of previous years, made it possible to construct a unified theory of the motion of inner planets (Mercury, Venus, Earth and Mars). In addition, new information was obtained on the relief and reflective properties of the surface of these planets.

As a result of observations of Venus, Mars and Mercury, which were regularly conducted in the USSR and the USA for two decades, extensive astrometric information was accumulated, on the basis of which the orbits of these planets were substantially refined and more advanced numerical theories were constructed to predict their motion.

The sensitivity of modern radars is increased several thousand-fold compared with 1961, which makes it possible to radar the inner planets at all sections of their orbits. The sensitivity of radars was also sufficient to conduct observations of the rings of Saturn, four Galilean moons of Jupiter and five minor planets (asteroids).

2. DETERMINATION OF THE ASTRONOMICAL UNIT AND THE RADIUS OF VENUS

The main result of radar observations of Venus, which is of paramount importance for astronautics,

is a cardinal refinement of the astronomical unit². Through the astronomical unit, all distances in the solar system are expressed, so the task of determining its absolute magnitude in kilometers has always been of great cognitive interest and has been in the center of attention of astronomers.

Its values, obtained by different optical methods in the period 1940-1960, ranged from 149.4 to 149.7 million km, i.e. the spread in values was about 300 thousand km. Prior to the beginning of radar measurements, the most reliable value was $149527000 \pm 10,000$ km, obtained in 1950 from observations of the movement of the small planet Eros during the period 1926-1945. With it the value of $149\,545\,000 \pm 20\,000$ km, obtained in 1960 from measurements of the radial velocity of the Pioneer-5 automatic station, was coordinated. However, as shown by radar measurements, these values were 50-70 thousand km less than the true value.

Such a mistake would lead to inevitable misses in the flights of spacecraft to the planets. Thus, when flying to Mars, the ship would be off the side the planet at a distance of 15 its radii, and when flying to Venus - at a distance of three of its radii.

The classical theory of planetary motion made it possible to calculate interplanetary distances through an astronomical unit with an accuracy of 10^{-5} - 10^{-6} . Measuring the interplanetary distance in kilometers using a radar, obviously, it was possible to determine the astronomical unit, with the same accuracy.

Even the first radar observations of Venus in 1961 made it possible to refine the value of astronomical unit by approximately 50 times. Its values, obtained in different countries and at different wavelengths, were in good agreement with each other, which indicated a high reliability of measurements.

A significant reduction in the errors in measuring the distance to Venus, achieved in the USSR in 1962 and 1964, made it possible to

increase the accuracy of the determination of the astronomical unit. However, for this purpose, it was required to refine the parameters of the orbits of Venus and the Earth, as well as the radius of Venus, but this could be done only on the basis of radar measurements over a longer time interval spanning several synodic periods of the Venus rotation (the synodic period is the time interval between the two lower connections, in which the distance between the Earth and Venus is minimal).

The possibility of refining the elements of the orbits was demonstrated already in the processing of the results of 1962 (Fig. 3). Then, along with the correction to the astronomical unit, corrections were also found to the position in the orbit and the radius of Venus (Table).

The radius of Venus on optical observations was determined at the level of the upper edge of the cloud layer and according to the estimates of astronomers was 6120 ± 8 km, the height of the cloud layer above the surface was unknown. For an accurate determination of the astronomical unit, it is very important to know the radius of the reflecting surface of Venus, as the distance to the

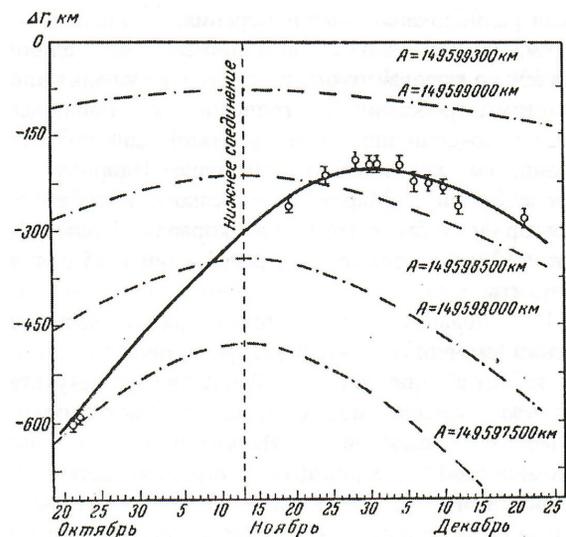


Fig. 3. Deviations (points) of the measured values of the distance from the calculated values along the observations of Venus in 1962 (in calculations it was assumed that the astronomical unit is 149599300 km, the radius of Venus is 6100 km). The curve (solid line) passing through these experimental points was calculated for astronomical unit of 149597900 km, corrections to the difference between the longitudes of Venus and Earth $+0''$, 5 and the radius of Venus of 6020 km. Dashed lines - curves calculated for other values of the astronomical unit (are shown on the right), but without taking into account the correction to the longitude and the radius of Venus.

²The astronomical unit of length is the average distance of the center of gravity of the Earth-Moon system from the center of the Sun.

Table

The values of the astronomical unit and the average radius of Venus, obtained in the USSR in different years

Observation interval	Astronomical unit (km)	Venus radius (km)
1961	149599300 ± 1000	-
1962	149597900±250	6020±50
1964	149598000 ± 130	-
1962-1964	149597886 ± 80	6046±15
1962-1975	149597888.9 ± 0.7	6052.3±0.3
1962-1980	149597889.0± 0.3	6050.1±0.1

Note. The astronomical unit values in the table are given over the speed of light 299792.5 km/s. If we use the refined value of the speed of light 299792458 ± 1.2 km/s, then the magnitude of the astronomical unit in the last definition will be equal to 149597868 ± 0.7 km.

front sections of this surface is measured radar-wise, and the theory of the motion of the planets gives the position of their center of mass, which is further by the radius value.

The processing of two cycles of measurements performed in the USSR in 1962 and 1964 made it possible to find corrections to the elements of the orbits of Venus and the Earth, which led to a further refinement of the astronomical unit and the radius of Venus.

Work on the simultaneous refinement of the astronomical unit, the parameters of the orbits of Venus and Earth, and the radius of Venus was carried out by the Lincoln Laboratory in the USA in 1966. As a result of the joint processing of the radar measurements of the USA and the USSR for the period 1962-1966, and optical measurements of the USA for the period 1950-1966. for the astronomical unit at a speed of light 299792.5 km/s, the value of 149597892.3 ± 1.5 km was obtained; for the radius of Venus is 6055.8 ± 1.2 km.

Subsequent measurements and analysis of radar data obtained before 1969 at the Lincoln Laboratory gave a value of 6050 ± 0.3 km.

The most accurate values of the astronomical unit and the radius of Venus in the USSR were obtained in 1976 and 1980 thanks to the construction of a more perfect theory of the motion of Venus and the Earth (see Table).

3. THE THEORY OF MOTION OF INNER PLANETS

Radiolocation observations of the planets have shown that even after the astronomical unit is refined, there are noticeable discrepancies between the measured distances and their values calculated by classical theories. The discrepancies reached several hundred kilometers (Fig. 4). Such errors in predicting the motion of planets according to classical theories made it difficult to solve the navigational tasks of astronautics, especially such complex ones as landing of the descent vehicle into a pre-selected area of the surface or launching an artificial satellite of planet with given parameters of its orbit.

In this regard, during the flights of automatic interplanetary stations, it was necessary, along with the trajectory measurements of the station position, to also conduct radar observations to precise the position of the planet.

It was necessary to create new, more accurate theories of planetary motion based on radar information.

Numerical theory of the motion of Venus and the Earth on the basis of radar observations of Venus in the interval 1962-1975 was built by the Institute of Radio Engineering and Electronics of the USSR Academy of Sciences and the Institute of Applied Mathematics of the Academy of

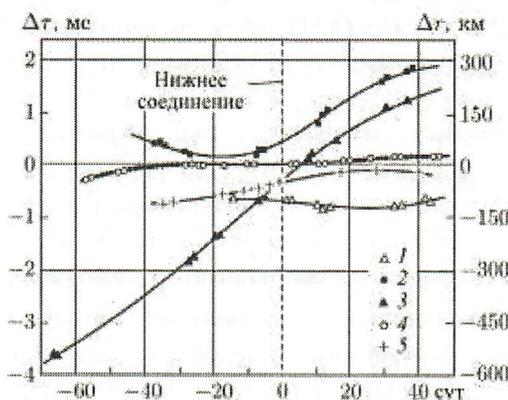


Fig. 4. Deviations of echo-signals lag from Venus and the corresponding distances from the values calculated in accordance with the classical theory (calculated in the calculation: astronomical unit -149597890 km, radius of Venus-6050 km), measured in different years in the USSR.

Sciences of the USSR together with a number of organizations in 1976-1978.

At the same time, the data of optical observations of Venus and the Sun made by the Nikolayev Observatory of the USSR Academy of Sciences and the US Naval Observatory were used, and the parameters of the movement of Venus-9 and Venus-10 artificial satellites of Venus in 1975

The problem was solved by numerical integration on the computer of a system of differential equations describing the motion of eight bodies in their gravitational field. The bodies were the Sun, Mercury, Venus, the Earth-Moon system, Mars, Jupiter, Saturn, Uranus. Estimates have shown that the influence of Neptune and Pluto in solving this problem can be neglected. Twelve elements of the orbits of Venus and the center of mass of the Earth-Moon system, as well as the astronomical unit and the radius of Venus, were included in the number of parameters to be determined.

The experimental verification of the constructed numerical theory, performed with the next radar of Venus in 1977, 1978 and 1980, showed that deviations of the measured distances from Venus from their predicted values in the numerical theory do not exceed 3-6 km (Fig. 5). At the same time, deviations of the measured distances from the forecast according to the classical theory, even with the precised astronomical unit, reached 500 km in this period.

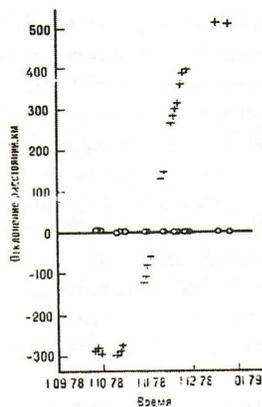


Fig. 5. Deviations measured in 1978 in the USSR, distances to Venus, from the calculated values, calculated on the basis of a new numerical theory (circles) and classical theory (crosses); in the calculation it was accepted: the astronomical unit is 149597888.9 km, the radius of Venus is 6052.3 km.

At the launch of the stations "Venus-11" and "Venus-12" in 1978 all navigational calculations were carried out on the basis of a new numerical theory. Measurements of the parameters of the movement of the stations, in turn, confirmed the high accuracy of this theory: the measured distances to them differed from those predicted by no more than 3 km.

In 1979, the Institute of Radioengineering and Electronics of the Academy of Sciences of the USSR jointly with other organizations processed radar observations of Mars for 1964-1971 and optical observations of Mars and the Sun for 1960-1975.

The determination of the orbits of Mars and the Earth was carried out by the same method used in the processing of observations of Venus. The parameters for determination were 12 elements of Mars orbits and the center of mass of Earth-Moon system. The accuracy of the forecasting of the motion of Mars on the basis of the solution obtained was verified by its radar observations in the USSR in 1980. The error in predicting the distance relative to the mean surface level of the planet on a two-month interval of observations varied monotonically from 13.6 to 21 km.

As a result of radar observations of Venus, Mars and Mercury in large sections of orbits in 1980, a new high-precision astrometric information was obtained in the Soviet Union. It substantially supplemented the results of previous radar observations of the planets, in particular Mercury and Mars. Thus, a real basis was created for constructing a unified theory of the motion of inner planets, i.e. for the simultaneous determination of the orbits of Mercury, Venus, Earth and Mars along the entire set of available radar and optical observations.

In 1980, in the Institute of Radioengineering and Electronics of the Academy of Sciences of the USSR jointly with a number of organizations the method and algorithms for constructing such a theory on the basis of the general theory of relativity were developed and on computer implemented. In this case relativistic differential equations were used to describe the motion

of inner planets. Among the planets, whose motion is described by a system of differential equations, Neptune was additionally introduced. When processing observations in the calculated values of the delay time of the reflected signal, relativistic corrections were introduced.

On the basis of the developed methodology, a unified relativistic theory of the motion of inner planets was created.

This problem was independently solved at the Institute of Applied Mathematics of the USSR Academy of Sciences and the Institute of Theoretical Astronomy of the USSR Academy of Sciences.

The construction of this theory was carried out on the basis of radar and optical observations of Venus and Mars, used earlier in the construction of particular theories of their motion; radar observations of Venus, made in the USSR in 1977 and 1978; the above-mentioned radar observations of Venus, Mars and Mercury in 1980; radar observations of Mercury in Arecibo in 1964-1965; optical observations of Mercury performed by the Nikolaev Observatory of the USSR Academy of Sciences, the United States Marine Observatory and the Greenwich Astronomical Observatory in 1960-1976. A total of 3.768 radar measurements of the delay time of the signal reflected from the planets and 7193 optical (angular) measurements were processed.

During processing, 28 parameters were determined: the elements of the orbits of Mercury, Venus, the center of mass of the Earth-Moon system, Mars, the astronomical unit, the radii of Mercury, Venus, Mars. For the radii of Mercury and Mars the values were respectively 2434.9 ± 1.1 km and 3394.6 ± 0.3 km.

The root-mean-square deviations of the measured distances from their values calculated from this theory are: for Venus (in the period 1970-1980) - 0.9 km; for Mars (in the period 1967-1980) - 2.5 km; For Mercury (in 1980) - 2 km. These deviations are largely due to the influence of the surface relief of the planets. Deviations of optical measurements from the forecast according to this theory range from 0.6"-1.2".

In order to estimate the limits of the applicability of Newtonian mechanics in the construction of such theories, all information was also processed without taking into account relativistic corrections. As might be expected, the coordination of the measured and calculated ranges has deteriorated markedly, systematic deviations have appeared in some sections of the orbits, reaching 390 km for Mercury, 12 km for Mars and 8 km for Venus.

The good agreement between the measured and calculated data achieved in the construction of a single relativistic theory of the motion of inner planets can be considered as an additional experimental test of the general theory of relativity.

It should be noted that radar observations of planets over a 20-year period (together with optical observations of planets and the Sun) made it possible to reduce the uncertainty of knowledge of the astronomical unit by almost 50,000 times and to increase the accuracy of the theory of motion of inner planets by one and a half to two orders. This allows us to predict now their mutual position with an error of less than 15 km. These fundamental results are a major contribution to the study of the dynamics of the solar system.

4. ROTATION OF VENUS AND MERCURY

Among the fundamental discoveries of radar astronomy are the results of a study of the rotation of Venus and Mercury. Three unexpected natural phenomena were discovered.

The first is that Venus, unlike all other major planets, rotates in the opposite direction, opposite to its rotation in orbit. The second is that the reverse rotation of Venus is not governed by the Sun, but by the Earth, so that at each approaching to the Earth Venus is almost exactly turned to the Earth by the same side. Third, for every two orbits, Mercury makes almost three turns around its axis. Previously, it was mistakenly thought, that Mercury makes one revolution around its axis during one revolution in orbit, that is, it always faces the Sun with the same side.

Before the radar observations, the period of rotation of Venus was estimated from 15 hours to 225 days (the definition was complicated by the cloud cover of Venus). The width of the frequency spectrum of the echo signal at the first radiolocation of Venus in 1961 showed that the planet rotates very slowly - with a period of more than 100 days.

More definite information was obtained by the next radiolocation in 1962, when due to a significant increase in radar sensitivity, the duration of observations was increased to two months. At that time, the Institute of Radioengineering and Electronics of the Academy of Sciences of the USSR and the Jet Propulsion Laboratory of the United States independently established that Venus rotates in the opposite direction (in comparison with the direction of rotation in orbit around the Sun), moreover, the period of its rotation around the axis lies within 200-300 Earth days. In these observations, the rotation was investigated from measurements of the width of the frequency spectrum of radio waves reflected from the planet upon irradiation of it with a monochromatic signal.

The width of the frequency spectrum is proportional to the magnitude of the angular velocity of the total relative rotation that could be seen from the Earth. This "visible" rotation consists of two components: own (sidereal) rotation and apparent, which is a consequence of the change in the mutual position of Venus and the Earth. The magnitude and sign (direction) of the second component vary with time; its values, depending on the dates of observations, are calculated on the basis of the known motion of the planets. In the lower connections, it is maximal (about 0.6 degrees per day) and has a positive sign; 21 days before the lower connection and 21 days after it the sign changes to the opposite one.

The character of the change in the total angular velocity of the visible rotation will be different depending on which sign has the angular velocity of the planet's own rotation. If it were positive, corresponding to a direct rotation, then the angular velocity of the total apparent rotation of Venus in the lower connections would be the largest and

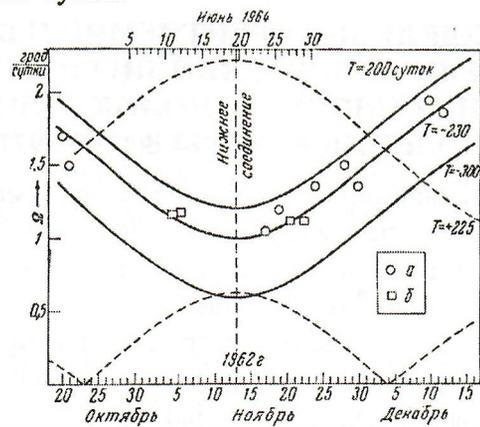


Fig. 6. Determination of the period and direction of rotation of Venus from observations in the USSR (circles) and in the USA (crosses) in 1962. The curves show how the total angular velocity of Venus's apparent rotation relative to the radar should vary with different values of the period T. The measurements indicate reverse rotation with a period of 200-300 days.

would decrease with departure from them. In fact, in all measurements near the lower connections, the opposite picture is observed; therefore, the direction of the proper rotation of Venus is the opposite (Fig. 6).

In subsequent observations, the rotation of Venus was investigated by other, more accurate methods, based on tracking the movement of radio waves anomalously reflected from areas detected on its surface. They appear on the frequency spectrum in the form of characteristic details with an increased spectral density (Fig. 7). Their position in the spectrum is determined by

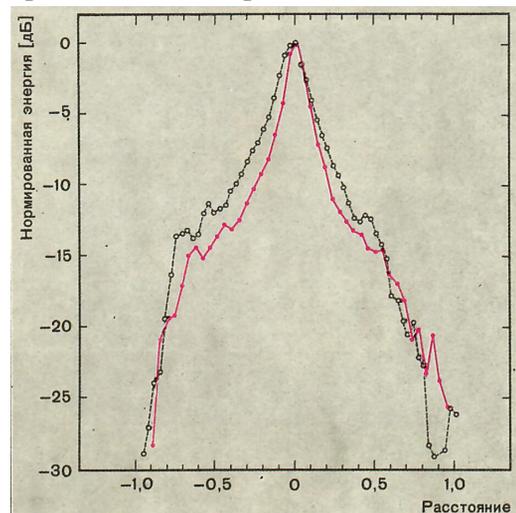


Fig. 7. Energy distribution of echo signals from Venus along the equator at monochromatic irradiation at a wave of 39cm (Crimea-Jodrell Bank, 28.01.1966, solid line) and 3.8cm (Heystek, 01.02.1966, dashed line). The distance from the center of the visible disk of the planet in fractions of its radius is plotted horizontally.

the ray velocities of the regions at the time of observation. Tracking the change in the position of parts in the spectrum over a long time allows us to determine not only the period, but also the direction of the axis of the planet's own rotation and specify the coordinates of the regions. In the joint Soviet-English observations of Venus in 1966, this method yielded a value of 243.9 ± 0.4 days for the period.

More precise values of the period of rotation of Venus were obtained by identifying the details of the spectrum from the anomalously reflecting regions in the lower compounds of different years.

In 1972, in 1975 and in the years of 1977, in the USSR, the moments of passage through the center of the visible disk of Venus two abnormally reflecting regions were measured, whose coordinates on the surface of the planet were determined by observations of 1964. The processing of these measurements gave a value of 243.04 ± 0.03 days. Similar results were obtained in the USA (Arecibo, 1964, 1967 and 1969 - 243.9 ± 0.1 days, Goldstone, 1962, 1964, 1966, 1967 - 242.98 ± 0.04 days).

These measurements show that the period of rotation of Venus in the opposite direction is very close to the synchronous (243.16 days), in which Venus would face the Earth by exactly the same side in each lower junction (**Fig. 8**). The duration of a solar day on Venus is 117 earth days. As shown by the analysis of radar observations, the axis of rotation of Venus is almost perpendicular to the plane of its orbit: the deviation from the perpendicular does not exceed 2° .

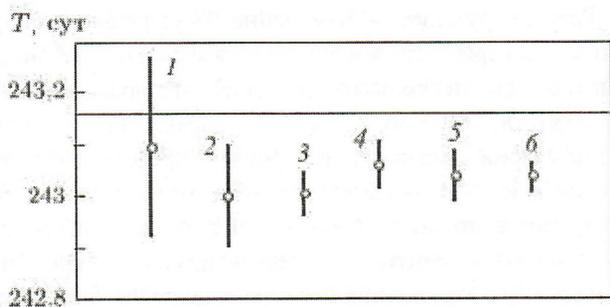


Fig. 8. Intervals of possible values of the period of rotation of Venus by radar observations in the USSR and the USA in different years: 1, 2, 3 - USA (1964-66, 1964-69 1962-67), 4, 5, 6 - USSR (1964-72, 1964-75, 1964-77).

Before radar studies of Mercury, as already mentioned, astronomers believed that the period of its rotation around the axis is equal to the period of revolution around the Sun (88 days) and that it always faces the Sun with the same side as the Moon to the Earth. However, the radar observations of Mercury performed in Arecibo in 1965 with different positions in orbit showed the fallacy of such a statement.

It was found that the period of rotation of Mercury is 59 ± 3 days. Subsequent detailed analysis of old sketches and photographs of the surface of Mercury led astronomers to a more accurate value of the period - 58.65 ± 0.01 days, which corresponds to orbital-rotational synchronization - behind 2 revolution on orbit, Mercury makes 3 revolutions around its axis.

It is necessary to explain that the previous error of astronomers was caused by the objective difficulties of observing Mercury by optical means, namely proximity to the Sun and small angular dimensions. Because of proximity to the Sun, astronomers were forced to observe Mercury once a year, during the period of its greatest angular distance from the Sun, when the conditions for observations are most favorable.

During the year, Mercury makes about four revolutions in orbit and, as now established, about six revolutions around the axis, rather than about four, as astronomers mistook earlier. At the same time, the earlier sketches and photographs of the surface of Mercury within their rather crude resolution are consistent with both the new and the old, erroneous, value of period.

5. SURFACE OF VENUS

Venus is surrounded by a dense cloud cover, opaque in visible, ultraviolet and infrared rays, so its surface is not available for observation even by the most sophisticated telescopes. Radio waves of the entire decimetric and adjacent part of the centimeter range, used in radiolocation, freely pass through the entire atmosphere of the planet. Due to this, its surface was accessible ("visible") for observations by radar.

Two decades ago nothing was known about it. The hypothesis of a continuous ocean of water

covering the entire planet seemed quite plausible. The hypotheses about a continuous ocean of oil and a continuous sandy desert were not rejected either.

The first reliable information about the surface of Venus was obtained only from the results of radar observations of 1961 and 1962.

Then for the first time it was found out that it is composed of hard rocks, the dielectric permittivity and density of which is about the same as that of terrestrial rocks on a silicate basis. This conclusion follows from the measurements of the coefficient of the back reflection of radio waves and the dependence of the scattering pattern on the angle of incidence on the planet's surface (the coefficient of back reflection is defined as the ratio of the energy of the received echo from the planet to the energy that would have been assumed had the planet been a smooth ideally conducting ball of the same size).

The average reflectance at 12.5, 39, and 68 cm wavelengths was in limit 11-16%, and its value during averaging over large areas changed very little from day to day (for example, in a two-month interval of observations in 1962 in the USSR, the change was not went beyond 11-18%), which indicated an isotropic structure of the surface on a global scale. The values of the reflection coefficient corresponded to the values of the permittivity 4-6, which are characteristic for soil density of 2-3 g/cm³. It is pertinent to note that the average reflection coefficients of the surfaces of Mars, Mercury and the Moon are about half that of Venus.

If the first observations of Venus were aimed at obtaining integral characteristics of reflection and elucidating the global properties of the surface, then later the main focus was already on identifying the distinguishing features of different regions. Abnormal areas of increased reflection were discovered back in 1962, and then re-examined in 1964. At the same time, a venereocentric coordinate system was introduced, whose zero meridian passes through the brightest region called the α -region (the latitude of the α -region is 30°).

In this system, it was possible to determine the coordinates of other detected anomalous regions, thereby creating a framework for constructing radar maps.

The first, still rather rough map of the reflective properties of a limited region with a resolution of hundreds of kilometers was compiled from observations in Heystock (USA) in 1969. A map of a larger region with a resolution of 50x50 km² was obtained from observations in Goldstone in 1969 and 1970. These maps show some large-scale continental formations of limited areas. Studies with a resolution of 10x10 km² of individual regions measuring about 1500 km in the equatorial belt of Venus began at Goldstone in 1972. In one of these regions, more than 10 ring craters with a diameter of 35 to 150 km were found. Works on the mapping of individual parts of Venus with a resolution of about 20 km were carried out in 1976 also in Arecibo.

During the radar observations of Venus great attention was paid to the studies of its relief. For such studies, the equatorial belt of Venus is available in the latitude interval $\pm 10^\circ$. The measurements of the surface heights profiles in this belt, performed at the Haystack and Arecibo stations in 1967-1970, covered eight complete revolutions of Venus relative to the Earth.

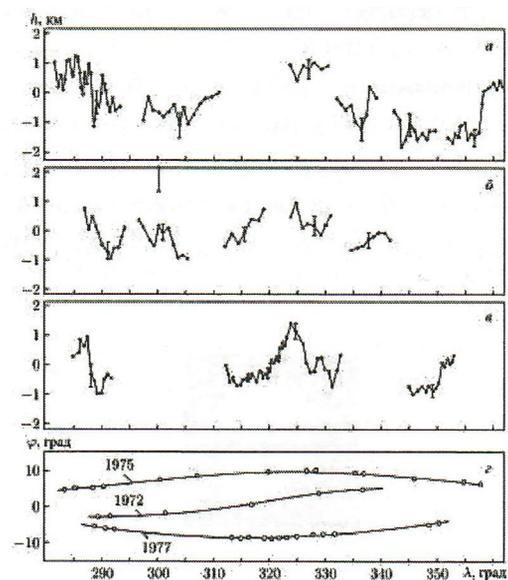


Fig. 9. Profiles of the heights of Venus surface, obtained in the USSR in 1972, 1975 and 1977. Below: the tracks along which measurements were taken.

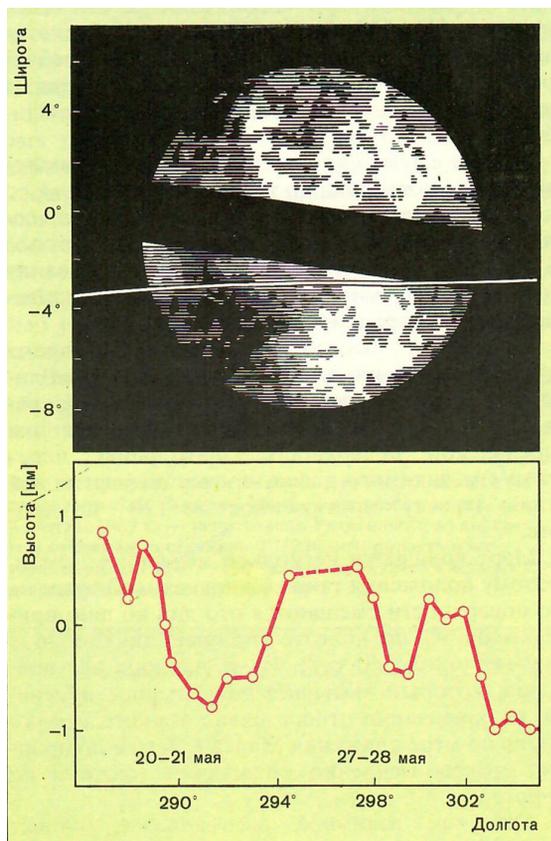


Fig. 10. Comparison of the profile of the altitudes of the surface of Venus (USSR, 1972) (bottom) with the results of the study of the relief of the circular section, along which the profile measurement trajectory passed (Goldstone, USA, 1973) (top). The track is marked by a white stripe. In the upper figure, high brightness corresponds to a large brightness; all brightness gradations - four (after 500 m)

The height profiles were obtained from measurements of the delay time of signals reflected as the planet rotates from the closest parts of its surface to the Earth. The resolution along the traces was 200-400 km, the accuracy of measuring the altitude variations was 0.2-1 km. There are two mountainous areas with a length of 4 and 2.5 thousand km, the elevations of which are respectively about 4 and 3 km. On the other longitudes, elevations do not exceed 2 km.

In the USSR measurements of height profiles were carried out in 1972, 1975 and 1977. The length of the traces was about 10 thousand km, the surface resolution along the traces was 40-200 km, the accuracy of the altitude measurements was 150-300 m (Figs 9, 10).

Simultaneously with the heights profiles along the slopes, the surface slopes (by the nature of the radio wave scattering) and the permittivity of the

soil (from the reflection coefficient measurements) of individual regions were determined - an analysis of these parameters together with altitude variations gives a more complete picture of the investigated areas.

The measured altitude differences on all routes do not exceed 2 km. Areas with a strongly cut profile are detected (for example, in the longitude interval 280°-290°), where altitude differences of 1-2 km are observed on the basis of 100-200 km, and extensive flat areas with a length of more than 1000 km (for example, in the vicinity of 305° longitudes and 350° at latitude + 10°). The mountain range at longitude 325° also has a length of more than 1000 km and a width of several hundred kilometers. The plain at longitude 350° resembles a giant basin composed of less dense material than its slope at a longitude of 355°. The surface characteristics of different regions vary within wide limits: the permittivity is from 2.7 (which corresponds to dry, sandy deserts on the Earth) to 6.6 (hard rocks), the average surface slopes are from 2.5° to 5°.

In the observations of Venus in the USSR, carried out in 1980 at a distance of 161 million km, the research route lay in another interval of longitudes and had a length of about 14 thousand km. It passed through the two mountain regions mentioned above. The greatest height of the first of them at the latitude of the route was about 4 km (at a longitude of 90°), the height of the second - about 3 km (at a longitude of 193°). For the second region, a detailed elevation profile with a longitude resolution of about 40 km was obtained (Fig. 11).

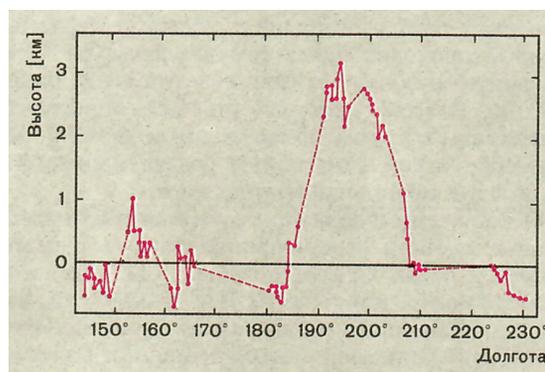


Fig. 11. Profile of the heights of the surface area of Venus (USSR, 1980). The measurement route runs from 2.4°S. (left) to 3.7°S. (on right).

6. SURFACE OF MARS

Realize the radiolocation of Mars is much more difficult than Venus radiolocation because of its greater distance from the Earth, smaller dimensions and relatively fast rotation. The speed of rotation of Mars is approximately 400 times greater than the speed of visible rotation of Venus in the lower connection. In most of the confrontations (with the exception of the great ones, which repeat only after 17 years), it approaches the Earth by only 80-100 million km. The detection of an echo from Mars at such distances requires approximately 500 to 1000 times more sensitive radars than from Venus in the lower connections.

However, if the sensitivity of the radar is already increased to the required value, then due to the rapid rotation of Mars and the greater inclination of its axis to the plane of the ecliptic (about 25°), the possibilities for a detailed study of its surface are much better than for the study of slowly rotating Venus.

Due to the rapid rotation during one night cycle of observations (by approach the Earth, Mars is only visible at night), say for 8 hours, the points of the Martian surface nearest to the Earth passing through the center of its visible disk, draw a line (route) of 120° in longitude.

Mars rotates somewhat slower than the Earth, so the positions of such (one-day) traces on its surface are shifted from day to day by about 9° in longitude (a full cycle of 360° takes about 40 days). Due to the inclination of the axis of rotation, which causes a continuous change in its orientation relative to the terrestrial observer as Mars and Earth move in orbits, the traces slowly move also and in latitude.

Since the mutual arrangement of planets in orbits in oppositions of different years varies, the traces of observations pass through different latitudes, the possible interval of which is $\pm 25^\circ$ from the equator.

The first series of radar observations of Mars at different wavelengths was performed in the 1960s: in the Crimea (1963, 39 cm), Goldstone (1963, 1965, 1969, 12.5 cm), Milestone (1965, 23 cm), Arecibo (1965, 70 cm), Heystack (1967, 1969, 3.8

cm). Traces of the closest to Earth points in these observations were in the northern hemisphere of Mars.

Studies have shown that the coefficient of back reflection of radio waves does not depend on the wavelength. Its average value is 0.07. It is about the same as that of the Moon, but somewhat larger than that of Mercury, and half as much as that of Venus. At the same time, local parts of the surface of Mars are differentiated in their properties much more than in Venus and Mercury. For example, the reflection coefficient varies depending on the coordinates on the surface in a wide range - from 0.03 to 0.14.

The most intense echoes are due to specular reflection from smooth surface areas in small neighborhoods of the nearest point. For these sites, the reflection coefficient values (12-14%) are approximately the same as for terrestrial rocks with a dielectric constant of about 4.5, which corresponds to a density of about 2.5 g/cm³.

The low reflectivity of some regions of Mars can be caused either by their large roughness (irregularities in the wavelength scale lead to a decrease in specular reflection), or by the low density of the surface material (greater absorption of radio waves and a smaller reflection coefficient) or by the combined action of these causes - a weak level of echo-signals did not allow to find out the true reason.

It should be noted that a small reflection coefficient (3-4%) corresponds to a matter density of only 0.8-1.0 g/cm³. Fine dust, covering these areas of the surface, can have such a density, for example. This dust, even under conditions of rarefied Martian atmosphere, can be suspended for a long time and can be a source of Martian dust storms.

Mars compared with other inner planets and Moon, has the smoothest surface.

The root-mean-square value of the slopes of irregularities on the scale of several tens of radio wave lengths varies for different areas in a wide range - from 0.5° to 6°, but its average value is about 2 times less than that of Venus, and 3 times less than that of Mercury and the moon.

The first radar measurements of the profile of the altitudes of the Martian surface along the 21st parallel of the north. were performed at Heystek in 1967. The hardware resolution by distance was 9 km, but the relative changes in altitude were measured to within 1 km.

Favorable conditions for radar observations of Mars were available during the great confrontation of 1971. Radar in this period was conducted in the Crimea, Heistek and Goldstone. The research routes passed in the southern hemisphere of the planet and covered the latitude from -14° to -23° . Along the traces were obtained profiles of heights and characteristics of reflection of radio waves by local areas of the surface. The total height difference from the highest mountains (about 8 km) to the lowest basins (about 8 km) in the investigated belt of latitudes was about 16 km.

Radar studies of reflective and physical characteristics in the southern hemisphere of the equatorial belt of Mars, performed in the 1970s, showed that the parameters of local sections of the surface vary within the same wide limits as in the northern hemisphere.

Interesting new information on the surface of Mars was obtained by its radar in the USSR in 1980. Along the 21st parallel of northern latitude, passing through epy Tharsis, Olympus Mons, Elysium, Syrtis Major mountain ranges, measurements were made of the height profile of the surface (Fig. 12) and the back reflection coefficient of radio waves

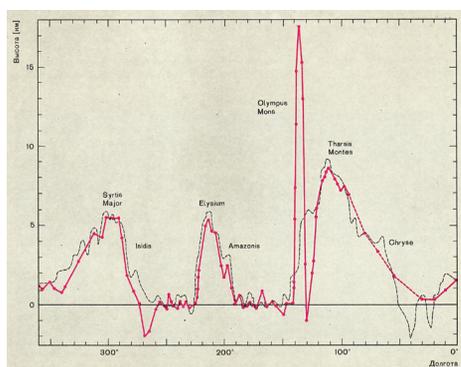


Fig. 12. Profile of the heights of the Martian surface along the 21st parallel of the north. (Crimea, 1980 - solid line, Haystack, 1967 - dashed line). The longitude resolution was mainly 4° (240 km); the region in the longitude interval 120° - 150° was analyzed in the Crimea with a resolution of about 1.5° (90 km).

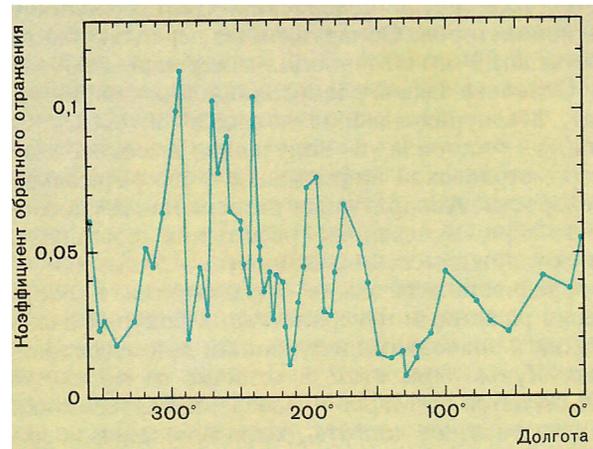


Fig. 13. Variations of the Mars backscattering coefficient along the 21st parallel of the north latitude (USSR, 1980).

(Fig. 13). The distance to Mars (100-135 million km) was measured to accuracy 0.6 km.

The measurement route passed along the northern slope of the mountain Olympus Mons, where the maximum height at this latitude was measured - 17.5 ± 1.5 km. The average steepness of the slopes of the mountain, estimated from the ratio of the height to the half-width of the foot at the zero level, is 3.6° . It is found that the western slope of the mountain is separated from the Tharsis mountain massif by a dent whose depth is 1 km below the average surface level. Another dent, up to 2 km deep, is at a longitude of 270° in the region of Isidis. Mount Olympus Mons and these dents were not previously recorded on the height profile obtained at Heistek at the same latitude (see Fig. 12).

The reflection coefficient of Mars along the path varies by more than an order of magnitude - from 0.01 to 0.12 (see Fig. 14). An abnormally low value in the mountainous regions of Olympus Mons and Elysium can be associated with a special structure of their surface: they have a small fraction of the areas oriented perpendicular to the incident ray of radio waves. Its greatest importance is on the Syrtis Major plateau; there is a strong mirror reflection from large-scale smooth regions.

7. SURFACE OF MERCURY

The radiolocation of Mercury is almost as difficult as of Mars. The minimum distances to Mercury in different lower connections vary within the limits of 80-100 million km, as in most of the oppositions

of Mars. The geometric area of its cross-section is 2 times smaller than that of Mars, the surface is several times more rough, as a result of which the fraction of mirror reflection of radio waves from its surface decreases. True, compared with Mars, it rotates 60 times slower, so that the extracting its echoes from receiver noise is simplified.

The first radar observations of Mercury at different wavelengths were performed in the Crimea (1962, 39 cm), Goldstone (1963, 12.5 cm), Arecibo (1964, 70 cm), Heisteke (1966, 3.8 cm). The main task of these and subsequent observations in the 60's was to obtain astrometric information about the speed of the planet and the distance to it. This information was necessary for the independent determination of the astronomical unit and the refinement of the orbits of not only Mercury, but also of Venus and the Earth, since Mercury exerts a noticeable gravitational influence on their motion, depending on its position in orbit.

Simultaneously with the astrometric data, the average (global) characteristics of the reflection of radio waves by the Mercury surface were obtained: the reflection coefficient and the energy distribution of the echo signals by delay and frequency.

The hardware resolution in the observations of the 1960s was insufficient to measure the heights profile and to study in detail the characteristics of the local sections of the Mercury surface. Such studies with a resolution of the surface at the equator of about 40 km and an altitude of about 1 km were achieved only in the early 1970s after increasing the sensitivity of radar. The observed altitude differences reach 3 km with an accuracy of ± 500 m.

The main task of radar observations of Mercury, performed in the USSR in 1980, was to obtain high-precision astrometric information about its distance and speed: The instrumental resolution for distance measurements was 1.2 km, with a velocity measurement of 5 cm/s.

The average statistical characteristics of the reflection of radio waves by the surface of Mercury are very close to the values obtained during the studies of the Moon. In this case, in

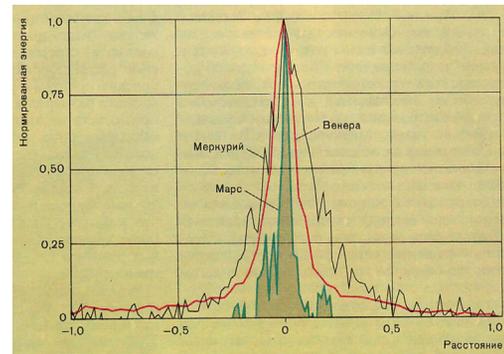


Fig. 14. Distribution of the energy of echo signals from Mercury, Venus and Mars along the equator at a wavelength of 39 cm (USSR, 1980). The normalized distance from the center of the visible disk of the corresponding planet in fractions of its radius is plotted on horizontally. The averaging time of the echo-signal energy is about 12 min. For Venus and Mars, the distributions have a smaller width than for Mercury, which suggests greater surface smoothness of the two planets.

contrast to what is observed on Mars and Venus, the characteristics depend little on the longitude, although the changes in the reflection coefficient by a factor of 2 depending on the longitude are also observed. Its average values at different wavelengths are in good agreement with each other and lie in the range 0.055-0.065 (for the Moon in the same range of radio waves they vary within 0.065-0.075).

Surfaces of Mercury and the Moon are similar in degree to their unevenness (roughness): as in the case of the Moon, the average slopes of the surface of Mercury increase monotonically with a decrease in the wavelength from 6° at 70 cm to 9.7° at 3.8 cm. The slope is about 1.5 times more than that of Venus, and 3 times more than that of Mars. The relative degree of roughness of these planets is clearly shown in **Fig. 14**.

8. THE RINGS OF SATURN

In the last century, it was theoretically and experimentally proved that the rings of Saturn consist of a huge number of particles that independently revolve around the planet along Keplerian orbits with different velocities. As for the size and composition of the particles, there was no definite answer to this question. On the basis of numerous observations near the infrared frequency range, it has recently been concluded that the rings of Saturn consist of the smallest particles of ice with a diameter of about $70 \mu\text{m}$.

However, there were arguments in favor of the fact that the ring is a conglomerate of ice fragments (or another substance covered with ice) of various sizes (from several meters to a centimeter or less).

More definite conclusions about the size and composition of the particles could be made only by the results of the radiolocation of the rings of Saturn.

The first echoes from the rings of Saturn were obtained with the help of radar in Goldstone at a wavelength of 12.6 cm in 1972-1973. A big surprise for the researchers of this planet was the unexpectedly large magnitude of the total area of particles participating in the reflection of radio waves back to the locator: it turned out to be equal to 68% of the geometric area of the rings visible from Earth. Such a value could only be obtained if the particle sizes in the rings were greater than 1 cm, which was in contradiction with the previous conclusions.

In late 1974 and early 1975, the radiolocation of Saturn's rings at Goldstone was performed at 3.5 and 12.5 cm wavelengths. In the latter case, the sounding signal was emitted from Arecibo, and the echoes were received at Goldstone.

From the analysis of all observations it follows that the reflection from the rings of Saturn is completely depolarized and does not depend on the wavelength. The joint processing of these results with radio astronomical and optical observations showed that the particles in the rings of Saturn are very rough, polyhedral pieces of water ice with an average transverse dimension of about 4 cm. The total echo signal from Saturn's rings is formed by multiple reflection of radio waves (almost lossless) from the particle surfaces.

New information was provided by the radiolocation of Saturn's rings in January 1976, conducted in Arecibo at a wavelength of 12.5 cm. The use of a modulated signal made it possible to separate the echo signals simultaneously by delay and frequency and to obtain a radial distribution of the particles along the annular zones. An appreciable number of particles was also found in the optically dark ring near the planet.



Fig. 15. *Antenna of the Center for Remote Space Communications, used in the USSR's planetary radar prior to 1980.*

The localization of echo signals by delay and frequency showed the absence of an echo signal from the space occupied by the planet itself (radio waves are absorbed by the vast atmosphere of Saturn).

9. PLANETARY RADAR

In the Soviet Union, radar studies of planets are conducted by the Institute of Radio Engineering and Electronics of the USSR Academy of Sciences in conjunction with a number of organizations. Planetary radar at a wavelength of 39 cm was created in 1961 on the basis of the antenna (**Fig. 15**) and the transmitter of the Center for Remote Space Communications in the Crimea. Subsequently, as already noted, radar was continuously improved to improve its sensitivity and measurement accuracy.

In 1962, the radar sensitivity was increased mainly due to the application of a low-noise paramagnetic amplifier (maser) on a ruby crystal cooled to liquid helium at 4 K (-269° C) at the input of the receiver. In the future, its increase was achieved by increasing the transmitter power, upgrading the antenna, applying more advanced methods for processing echoes using computers and improving the measuring equipment complex. Radar sensitivity was radically increased in 1980 due to the use of a new antenna with a mirror diameter of 70 m (see Fig. 2) and more powerful transmitters.

In comparison with conventional radiolocation planetary radiolocation has a number of distinctive features.

The received echo signals from the planet are very weak. To separate them from the fluctuation noise interference of the receiving equipment is required their long-term accumulation and averaging. With a very weak signal they can reach tens of hours (the ratio of the echo-signal energy to the fluctuation noise interference at the output of the accumulator increases in proportion to the square root of the accumulation time).

The reception of the signal reflected from the planet takes place after its emission through a considerable time, unusual for ordinary radiolocation, during which the radio waves propagate until planet and back (for example, for Venus it ranges from 4.5 to 29 min, and for Mars reaches 45 min). In connection with this, the radar observation session of the planet includes two time intervals: in the first one, the probing signal is continuously radiated to the planet, in the second is received the return signal reflected from it.

The position and motion of the planet relative to the radar can be calculated with great accuracy in advance, even before the beginning of the observation session. When the first radar of Venus was conducted, the distance to it could be predicted with an accuracy of ± 20 thousand km. Now, after accurating the astronomical unit and constructing a more accurate theory of the motion of inner planets, the distance to them is predicted to accuracy 10-15 km.

High accuracy of the preliminary calculation allows measuring the delay and Doppler shift of the echo frequency based on the hardware counting (playback) of their predicted values and determining deviations from the forecast, which drastically reduces the measurement interval when processing echo-signals.

Finally, it must be specially noted that the relative accuracy of measurements in the planetary radiolocation, required and already achieved is several orders of magnitude higher than in conventional radiolocation; for example, the

distance to the planets is now measured with relative accuracy up to $2 \cdot 10^{-9}$, while the accuracy required for conventional radiolocation does not exceed 10^{-6} .

Further, we explain in more detail the principle of construction and operation of the radar.

The radar is built on the principle of a coherent-synchronous system: in it all the oscillations necessary for the formation of the emitted signal, of the receiver's heterodyne signals, of reference signals in the processing system of the received echo signals, as well as signals for counting the time intervals in the program-temporary device are synthesized from one highly stable reference signal of the master oscillator by multiplying, dividing and converting frequencies.

The frequencies and phases of all oscillations at such a locator structure are related to each other by precisely known relationships and have a high stability, determined by the stability of the etalon signal, which allows obtaining a high accuracy of frequency-time measurements. As a master oscillator in the 1960s, a precision quartz oscillator with a frequency stability of about 10^{-9} was used, and in the 70s a hydrogen standard of frequency with stability was better than 10^{-12} . The true value of its frequency is also known with the same accuracy, which is especially important for determining the exact time intervals for measuring the delay of echoes.

The program-temporary device (chronizer) allows to count the predicted delay for the delay of echoes with a duration of up to 10.000 s with a resolution of $0.1 \mu\text{s}$ by counting the number of periods of the etalon signal with a frequency of oscillations of 10 MHz.

A digital synthesizer with programmable frequency variation gives the calculated Doppler shift with an accuracy of 0.01 Hz in the range of ± 300 kHz.

For the simultaneous measurement of the delay and the frequency of echo signals in the radar of the USSR, linear-frequency-modulated radio signals (LFM signals) have been applied since 1962, the frequency of oscillations of which periodically varies according to a sawtooth linear law (**Fig. 16**).

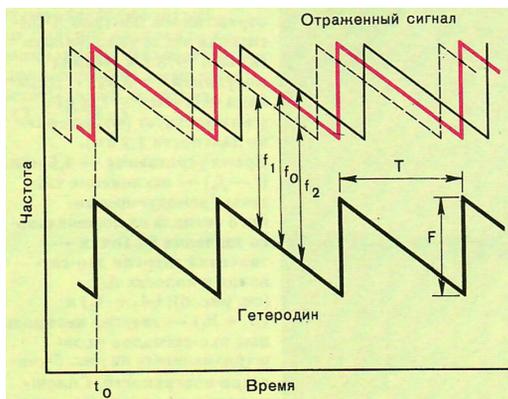


Fig. 16. Frequency change at linear frequency modulation (LFM) of the reflected signal at the receiver input (top) and the heterodyne signal (bottom). t_0 is the calculated delay time of the echo signal; f_0 - rated frequency; f_1 - frequency below the nominal, and f_2 - above the nominal; T is the modulation period; F is the frequency deviation.

In the United States, signals with phase-pulse code modulation are used for these purposes. The use of linear frequency modulation turned out to be very effective after the development of a special generator in 1962, providing a strict linearity of frequency variation.

It was suggested to synthesize a modulated oscillation from sufficiently short sinusoid segments of an increasing or decreasing frequency that are fused at times of simultaneous zero crossing. A set of fused sinusoidal oscillations is formed from a reference signal, which results in high stability and repeatability of the synthesized signal form. In the new radar system, the LFM signal is formed on the principle of direct digital synthesis using integrated microcircuits.

The motion of the planet relative to the locator leads to a change in the delay of the echo-signal. An original way of taking into account the motion of the planet was proposed, which consists in the fact that the correction for the predicted value of the Doppler shift, reduced to this frequency, is introduced into the frequency of the etalon oscillations from which the modulated signal is formed. In this case, each period of the radiated signal varies according to the expected current value of planet velocity, and the period of the received reflected signal remains constant as from the fixed target, which allows to make its accumulating and averaging without degrading the accuracy of the delay measurement.

The beginning of modulation of the probing chirp signal emitted in the direction of the planet is "tied" to the signals of a single universal time. During the reception of the echo-signal, the chirp signal is repeatedly generated and fed to the receiver heterodyne, where it is used as the reference heterodyne oscillation for demodulating the received signals; while the beginning of its modulation is delayed by the predicted propagation time of radio waves until planet and back.

The surface of the planet can be considered as a set of independent point-like reflectors, which are located at different distances from the locator and have relative to it a different speed of motion, caused by the rotation of the planet. Therefore, the echo-signal from the planet is the sum of the partial echoes with different delays and Doppler offsets of frequency.

The change in the frequency of each of the partial echoes at the input of the receiver (see Fig. 17) repeats the change in the frequency of the emitted chirp signal with a delay determined by its propagation time. The frequency of the heterodyne signal varies according to the same law - the beginning of its modulation corresponds to the calculated instant t_0 of the arrival of the echo signal from the closest parts of the planet's surface to the Earth. The frequency of the signal at the output of the receiver is equal to the difference between the frequencies of the echo signal and the local oscillator; it depends both on the actual lag of the partial echo signal and on its Doppler bias. If the actual delay values and Doppler offset values are equal to the predicted values, the frequency at the receiver output is equal to the nominal value f_0 .

If the echo signal arrives a little earlier, then the output frequency will be lower, than the nominal frequency (f_1) most of the time; if later, it is higher than nominal (f_2). In the general case, the frequency deviation at the receiver output, from the nominal value will be proportional to the difference between the actual delay of the partial echo signal and the predicted delay of the chirp heterodyne signal.

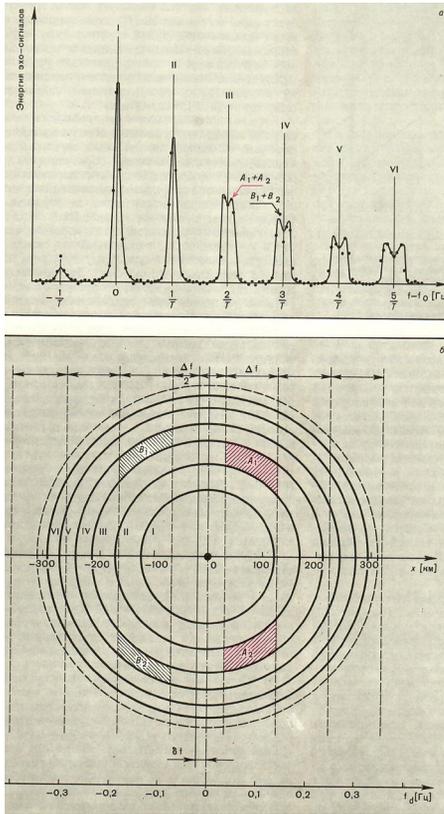


Fig. 17. *a* is the spectrogram of the Venus reflected LFM signal after demodulation (Crimea, 1978). The modulation period is $T = 0.512$ s. The frequency deviation is $F = 128$ kHz (corresponds to a resolution of 1.2 km). The averaging time is 4.5 min. $(f - f_0)$ is the deviation of the frequency f of the demodulated signal from the nominal value f_0 . Points are the energy values of the echo-signals in the Δf bands (see Fig. B); $(A_1 + A_2)$ and $(B_1 + B_2)$ - the energy of the partial echo-signals from the shaded in Fig. b surface areas. The solid line is a theoretical spectrogram for an isotropic-reflecting surface. Roman numerals are the numbers of echo-signal sub-spectra from individual ring zones of range (see Fig. b). Vertical lines are half the summary energy of the echo-signal in each of the subspectra. *b* - the central part of the visible disk of Venus, responsible for the reflection of the echo-signal, the spectrogram of which is shown in Fig. a. Circles - boundaries of resolved ring zones (Roman numerals), separated by 1.2 km (in range). Vertical dashed lines are the boundaries of bands separated by frequency with a resolution of $\Delta f = 0.122$ Hz, x is the distance in the equatorial direction, f_d is the Doppler shift caused by the rotation of the planet. δf is the group shift of the subspectrums in frequency due to inaccurate compensation of the Doppler shift caused by the motion of the planet in orbit. A_1 and A_2 (B_1 and B_2) are parts of the surface that are solvable by delay and echo frequency together (see Fig. a).

From each input partial echo at the output of the receiver, a periodic output partial signal is generated. The summary output signal resulting from the conversion of all partial echoes from disparate points on the surface is also periodic

(with the same period). The spectrum of the frequencies of summary output signal, formed as a result of interference of the spectra of individual partial signals (Fig. 17a), has a line structure (as in any periodic signal). The spectral lines are located at frequencies that are separated from the nominal frequency at intervals that are multiples of the frequency of repeating the sawtooth modulation.

It may seem that the spectrum (since the delay of individual partial echoes changes continuously) must also be continuous. However, as the detailed examination shows, this is not so. It turns out that when decomposed into the spectrum, the energy of the partial echo-signals, the frequency of which should have hit in the gap between the spectral lines, is distributed to the nearest discrete spectral lines.

In Fig. 17a shows, as an example, the spectrum of signals reflected from Venus after heterodyning. If Venus had not rotated, then this spectrum, as from a periodic signal, would have been lined (vertical lines in Fig. 17a).

In the case of a "nonrotating" Venus, the left spectral line is due to echo-signals reflected from the zone of Venus, closest to us (zone I in Fig. 17b). Next, the spectral line - from the ring zone II, located somewhat further, etc. Strictly speaking, the zones that cause individual spectral lines are not separated by a sharp boundary: they overlap one another in part.

In the case of the rotation of Venus, the spectral lines are blurred due to the fact that the frequencies of the partial echoes from the elements of the zone approaching the locator will increase somewhat due to the Doppler shift, and the retreating ones will decrease. In Fig. 17b show the values of these displacements for the case of the spectrum in Fig. 17a. Clearly, the larger the number of the zone, the greater the extension of the line.

Studying the spectrum, it is possible to separate the reflections from different parts of the planet: Thus, the reflection from the shaded elements in Fig. 17b causes the spectral components shown in Fig. 17a with arrows.

In the case when the axis of rotation of the planet is exactly perpendicular to the direction of the locator, it is not possible to divide the signal from the surface elements symmetrically lying relative to the equator. When, however (as is the case with Venus), the axis is not perpendicular, the separation is possible by location the planet in different parts of the orbit.

The average frequencies of all subspectra correspond to reflections from the points of the surface for which the Doppler shift caused by the rotation of the planet is zero. Therefore, by group shifting of the average frequencies of the subspectra from their nominal positions, known with high accuracy (better than 0.01 Hz), it is possible to determine the uncompensated part (deviation from the prediction) of the Doppler shift caused by the orbiting motion of the planet. In this case, an unambiguous determination can be obtained only if the deviation from the forecast does not exceed half the frequency of the repetition of the modulation.

In the radar of the planets, two deviation values (the total deviation of the frequency) were mainly used: 128 kHz, at which 8 μ s delay resolution (1.2 km in range) is provided, and 32 kHz, at which it is 32 μ s (4.7 km in range).

The modulation period is selected in such a way as to ensure the separation of the spectra of the individual zones. With the radiolocation of Venus and Mercury, modulation periods from 0.06 to 4 s were used, with Mars radiolocation from 0.008 to 0.064 s.

The system for processing the echo-signal using probing chirp signals is simpler than using other types of modulation (pulse, phase-pulse, etc.), since it reduces to a single-channel system of spectral analysis. Other types of modulation require multi-channel processing systems.

Operative processing of signals reflected from the planet during their reception for the purpose of controlling the operation of the radar and correcting the predicted delay is performed by a specialized digital device that allows analyzing the current spectrum of the received signal in

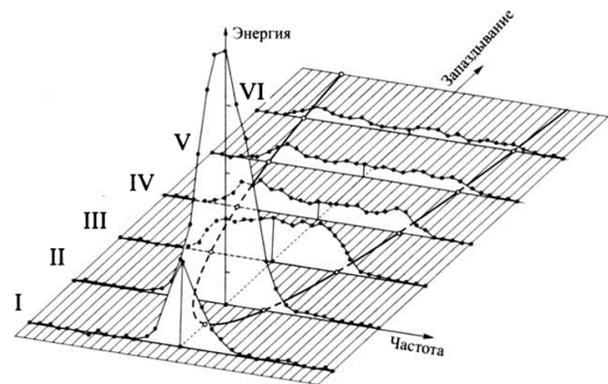


Fig. 18. Two-dimensional distribution of the energy of Venus reflected radio waves by delay (range) and Doppler frequency shift (along the equator) (USSR, 1970).

the entire frequency band with a resolution of 0.25 to 16 Hz.

Complete processing of the received signals is carried out with the help of a general-purpose computer. For this, in the reception process, they are first recorded on magnetic tapes in analog and digital forms. In the analog version, simultaneously with the signal, a reference etalon oscillation is also recorded, by means of which time and frequency calibration is performed while processing the registered echo-signals.

At the first stage of full processing in the computer, a spectral analysis of signals with a frequency resolution of 0.122 Hz is performed for the radiolocation of Venus, 0.5 Hz for Mercury and 16 Hz for Mars. As a result, 256 (or 512) coefficients of the Fourier expansion of the energy spectrum are obtained and synthesized two-dimensional energy distribution of the reflected signals on the delay and frequency (**Fig. 18**).

At the second stage, the resulting two-dimensional distribution is analyzed in order to extract the information of interest to us.

10. CONCLUSION

At the Institute of Radioengineering and Electronics of the USSR Academy of Sciences in the period 1961-1982, a new direction of observational astronomy - planetary radiolocation - was developed. The work was carried out with the help of a specially designed planetary radar ($\lambda = 39$ cm) of appropriate sensitivity, as well as developed methods and an echo-signal processing program. The first

successful radiolocation of Venus made it possible to drastically accurate the basis of all calculations - an astronomical unit approximately 100 times: the value 149597889.0 ± 0.3 km was obtained.

A new high-precision astrometric information was received for Venus, Mars and Mercury, which together with optical observations allowed the construction of a single relativistic theory of the motion of inner planets (Mercury, Venus, Earth and Mars).

In addition, new information was received on the relief and reflective properties of the surface of these planets, the radius and nature of the rotation of Venus, its surface, as well as the surfaces of Mercury and Mars.

The size and composition of the particles of Saturn's rings were also studied.

These fundamental results are a major contribution to the study of the dynamics of the solar system.

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