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RESULTS OF RADAR LOCATION OF PLANETS
(REVIEW PAPER)

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RESULTS OF RADAR LOCATION OF PLANETS*

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SUMMARY

During the short period of time since 1961, when the first successful radar observation of Venus was conducted, a new method enabled us to obtain important data on the motion and the nature of planets. From the point of view of astronautics, the basic result of radar location of planets is the refinement of the astronomical unit, which, according to measurements conducted in USSR and agreeing with measurements of USA and England, is equal to $149.598.000 \pm 130$ km. With the aid of radar location the presence of errors was revealed in the existing theory of planet motion.

Another important result is the determination of rotation periods of planets. Radar location permitted to establish that Venus has a reverse rotation with a period of 243 days and that the rotation period of Mercury is 59 days (in the right direction). The radius of the hard Venus surface was also determined.

Radar investigations have shown that the reflection of radiowaves by planets has a specular character. It was possible to establish on the Venus' surface local regions with increased reflectivity of radiowaves, which allowed us to compose the first chart of the surface of this planet.

Investigations of reflectivity of Mars' surface in radiowaves together with data on its thermal qualities point to the fact, that dark regions of the planet could have the same composition as the terrestrial rocks, while the cover of bright regions constitutes a thin layer of a tiny sandy dust. Apparently the dark regions of Mars represent the elevations.

The radar location enabled us to detect the absorption of centimeter radiowaves in Venus' atmosphere. Data on radar investigations point to the absence near Venus of a noticeable magnetic field and a very powerful ionosphere, which was confirmed by the flight of automatic interplanetary stations.

* * *

Only seven years have passed since the first successful radar investigations of Venus [1-4] have taken place in USSR, USA and England, while the new method of investigation of the solar system has already allowed us to

* Additional text of report at the Jubilee Session of Scientific Council on the problem of "Radioastronomy" AN SSSR, dedicated to the 50th October Anniversary (Gor'kiy, 1967).

obtain a series of valuable data regarding the motions and the physical nature of planets. During this period radar investigations of Mercury, Mars and Jupiter were undertaken, but the most intensive and fruitful turned out to be those of Venus.

REFINEMENT OF ASTRONOMICAL CONSTANTS

The basic result of radar investigations of Venus, of paramount value to cosmonautics, is the refinement of the astronomical unit. The radar method of determination of the astronomical unit is based on measurement of distances to the nearest region of the planet according to the retardation of reflected radiowaves. The achieved precision of measurement constitutes at the present time 1 - 2 km, if one eliminates from the investigation the error in the assumed value of the speed of light. The magnitude of the astronomical unit, determined from the measurements conducted in USSR from 1961 to 1964, and agreeing with those of USA and England, is equal to 149.598.000 km with a RMS error of 130 km (including the error in the speed of light) [5].

It was considered till the beginning of radar investigations that the most reliable value of the astronomical unit was that obtained by Rabe from optical observations of motions of minor planet Eros [6]. As is shown by radar data, this value is by 66.000 km smaller than the true one. Recently Rabe made known that he detected an error, upon whose removal the observations of Eros lead to the same value of the astronomical unit that was obtained with the aid of radar [7]. The 12th General Assembly of the International Astronomical Union in 1964, recommended for use in astronomical annals [8] the value of the astronomical unit obtained by the radar method. The refinement of the astronomical unit made possible the flight over the assigned distance and the hitting of planet's surface by interplanetary stations. If, during the flight of "VENERA-4" the value of the astronomical unit considered as most reliable prior to radar measurements had been used, it would have led to a miss by 3 Venus' radii.

Radar measurements conducted in USSR [9] and USA [10,11], have shown

that even after the introduction of correction into the value of the astronomical unit, there still remain considerable divergences between the actual position of Venus in orbit relative to Earth and that computed one on the basis of standard ephemerides. The basic part of these divergences, reaching several hundreds of kilometers, may be eliminated, if we are to assume that the difference of heliocentric longitudes of Venus and Earth differ by 0.5" relative to the ephemeral value, computed according to Newcomb's analytical theory, taking into account ~~Dancomb's~~ corrections of the elements of Venus' orbit. An analogous displacement was also revealed in the relative position of Mercury [10].

Investigations were stipulated in the Soviet Union and in the USA, on simultaneous refinement of several astronomical constants on the basis of radar data. This work was to the greatest extent completed at the Lincoln Laboratory of Massachusetts' Institute of Technology under the guidance of Shapiro [12]. For the refinement of astronomical constants data on radar observations of Venus and Mercury, obtained in USA and USSR, were used, alongside with the data on optical observations by the U.S. ~~Marine~~ ^{Naval} Observatory, for a great length of time. The value of the astronomical unit, expressed in light seconds, and consequently, error free in the speed of light, was found to be equal to 499.04786 ± 0.000005 sec. For a speed of light value of 299792.5 km/sec this yields 149597892.3 ± 1.5 km.* The orbit elements of Mercury and Venus and the Earth-Moon system's barycenter, the radii of Mercury and Venus, as well as the masses of inner planets were simultaneously obtained.

In so far as the Moon influences the position of the Earth's mass center, and consequently also the position of measurement point, radar observations can be used for the refinement of the mass of the Moon. According to [12], the Earth to Moon mass ratio constitutes 81.303 ± 0.005 .

* The RMS value of the formal error without taking into account the accuracy of the assumed value of the speed of light.

DETERMINATION OF ROTATION ELEMENTS AND THE DIMENSIONS

OF VENUS AND MERCURY

A very important result of radar observations of Venus, is the establishment of rotation period's magnitude and orientation of planet's axis. The measurements of the latitude variations of the reflective signal's spectrum, conducted in USSR in 1962 [9], allowed to establish that Venus has a reverse rotation (in relation to the planet motion around the Sun) with a period around 250 terrestrial days, while the rotation axis is perpendicular to the orbit plane. Analogous results were obtained in USA [13] and also in England [14]. Subsequently, more precise measurements [15-17] have shown that the rotation period is somewhat less than 250 days.

In the reactive engine laboratories the rotation of Venus was more precisely determined by the displacement of certain planet surface regions having a higher reflectivity in radiowaves. Having identified a specific region in two lower conjunctions, Goldstein obtained refined values of the period 242.6 ± 0.6 days and coordinates of vector rotation: right ascension $98 \pm 5^\circ$, declination $-69 \pm 2^\circ$ [18]. While observing two regions in lower conjunctions of 1962, 1964 and 1966, Carpenter obtained a period value of 243.24 days with an error of only 0.10 days [19]. Within the precision limits, the results of rotation period measurements coincide with the value of 243.16 days, ^{for} which Venus must face the Earth from one and the same side in each lower conjunction. In the interval between the conjunctions, recurring as an average every 583.92 days, a ground observer would be seeing four complete Venus revolutions, if its surface was cloud free. In connection with this coincidence, the possibility was examined regarding Venus rotation synchronization by the Earth's orbital motions by means of tidal forces [20,21].

The North pole of Venus, whence the planet's rotation should be seen toward the side of counterclockwise motion, actually finds itself in the Southern hemisphere provided the equatorial system of coordinates is used. The duration of average solar days on Venus is of 116.8 terrestrial days.

Although attempts to determine the period and axis orientation from optical observations were undertaken a long time ago, only the radar method enabled us to obtain reliable data on Venus rotation. The details observed on Venus' disk in the ultraviolet rays, of which the displacements were utilized for the determination of rotation, are apparently related to the upper boundary of the planet's cloud layer [22]. Their motion and variation are conditioned by the winds of the upper atmosphere with speeds possibly reaching 100 m/sec. [23].

Quite unexpected was the result of Mercury observations, whose rotation period was assumed to be equal to 88 days, just as the revolution period around the Sun. The observations by Pettingill and Dyce [24,17] at the Ionosphere Observatory in Aresibo show that the Mercury rotation period constitutes in reality 59 ± 3 days in the right direction. After this discovery, it was possible to show that Mercury, whose orbit differs by great eccentricity at nonspherical mass distribution, can have steady synchronous rotation period of 58.65 days, constituting $2/3$ of planet's rotation period [25]. This does not contradict previous optical observations, which, as was demonstrated lately [26], admit an ambiguous interpretation.

Radar permitted to determine also the radius of the hard, radiowave-reflecting Venus' surface. The optical methods such as, for instance, observations of Regula occultations, give the radius of the upper edge of planet's cloud layer. According to Vaucouler's estimate [27], it is equal to 612 ± 8 km. The surface radius could be obtained together with the astronomical constants from radar measurements of the distance to the planet. In the Soviet Union the latter yielded the value of 6020 km [9], which as was to be expected, is smaller than the visible radius; however, the error of this estimate had the same magnitude that was required for radius correction.

A very reliable result was obtained by Shapiro [12], who used the radar data of several observatories from 1961 to 1966, whereupon observations completed at the Ionosphere Station in Aresibo, encompass the entire Venus' orbit from the lower to the upper conjunctions. The radius of Venus turned

out to be 6056 ± 1.2 km.

The dimension of the radius may be determined directly, provided the distances to planet's center and to the nearest surface region are known. Such measurements were accomplished during the flight of AIS "Mariner-5", which passed at the distance of 4100 km from the planet's surface in October 1967. The planet's mass center was the geometrical focus of station's flight trajectory, and its position could be determined from the trajectory measurements. The position of the nearest region of the surface was measured with the aid of a radar locator in Aresibo. According to these measurements the Venus' radius constitutes 6054 km. According to radar data, the radius of Mercury is equal to 2434 ± 2.2 km [12].

SURFACE CHARACTERISTICS OF VENUS AND MARS

The first reliable data on the very surface of Venus, were obtained as a result of investigation of reflection characteristics' location in radiowaves, as well as from the measurements of differential polarization of planet's intrinsic radiation by Kuz'min and Klark [28]. At the present time radar observations are conducted in the wavelengths from 3.6 cm to 7.84 m. The reflectivity (albedo) of Venus in the waves longer than 20 cm, remains practically constant. The energy density of radiowaves reflected back to locator, constitutes in this range about 15% of the magnitude, which would have been observed had the planet's surface been mirror-smooth and ideally conducting [29,9,2,30-32]. It is about twice as much as the albedo of the Moon [33].

The polarization of the basic fraction of energy of Venus-reflected radiowaves corresponds to specular reflection. No more than 5-10% of the entire energy returning to the locator [34,16,35,9] is subject to depolarization. The specular character of reflection, manifests itself in that mainly a small zone at the center of the visible planet's disk, where waves are incident almost perpendicularly to the surface, reflects back to the locator. The diameter of the effectively reflecting zone is 10 times smaller than that of the planet. Such character of reflection may be expected from

an undulated dielectric surface, whose roughness dimensions and curvature radii are much greater than the wavelength [36]. The most reliable value of the inclination angles along Venus' surface should constitute about 3° . On the Moon this quantity is somewhat greater, say about 4° , for measurements in the 68 cm wave.

As a consequence of planet's rotation various regions pass near the center of the disk. This allows us to investigate the variations of surface's reflectivity in the equatorial zone. As a rule, the albedo variation of Venus, averaged over the part of surface this method allows, does not exceed two times [16,29,9,30].

The magnitude of the dielectric constant of Venus' surface, determined by the energy of specular reflection in the decimeter band, lies within the limits from 3.5 to 6 [37]. About the same value of the dielectric constant is found in terrestrial rocks in dry state over a silicate substratum.

A direct interpretation of differential polarization measurements of Venus' intrinsic radiation in the 10.6 cm wave [28], resulted in a smaller dielectric constant (2.2 ± 0.2). However, upon introduction of corrections for radiation absorption in Venus' atmosphere and surface roughness, the author of [38] succeeded in coordinating this determination with the radar result.

Local regions on Venus' surface, of hundreds and thousands of km extent, and having an increased reflectivity, could be revealed with the aid of radar location [39,29,40,17]. The Doppler shift variations of radiowaves reflected by these regions, are the consequence of the fact that these regions are part of hard surface and rotate with the planet. The very same regions could thus be identified on different wavelengths and in different conjunctions [41,16,18,42].

For a non-central position, the regions' brightness could be 5-10 times higher than the surrounding localities. The indicated regions have an increased

reflectivity in depolarized waves too [41,15,16,35]. Apparently the surface has there a rougher structure, which increases the intensity of the reverse reflection, when these regions are situated far off the center of planet's disk. An analogous phenomenon was revealed on the Moon in the regions of great radiant craters [43,44].

The discovery on the surface of Venus of regions with increased reflectivity, opened up the possibility to conduct with the aid of radar the cartography of the surface and the refinement of Venus' rotation elements, just as for the planets, whose surface is accessible to optical observation.

By comparison with Venus, radar investigations of Mercury and Mars are complicated by a greater distance, smaller planet dimensions and (in the case of Mars) by faster rotation, resulting in a strong blurring of the reflected signal's spectrum. The radar observations of Mercury were conducted for the first time in the Soviet Union [45] one year ahead of USA [46], while those of Mars were done simultaneously [47,48].

The Mercury albedo in the 3.8 to 70 cm waves constitutes 5-7% [41,45, 29,30]. It has approximately the same reflection characteristics as the Moon.

The character of wave reflection during Mars' rotation, varies substantially more than in the case of Venus. Some regions of martian surface have great specular properties: when such a region is found to be at the center of the visible disk, the dimensions of the zone, providing the basic reflection, does not exceed $1/20$ - $1/25$ of planet's diameter.

The albedo of Mars varies from 3 to 13% [49] and is also substantially stronger than that of Venus. The albedo variations in different wave-lengths correlate between themselves [50,51]. These variations may be compared with the details of the visible disk. It was found that, as a rule, high albedo values are observed, at the time when the dark regions of Mars (maria) [48,50] cross the center of the disk.

In the radioband the dark regions of Mars have approximately the same reflectivity as the terrestrial rocks, the density of which is about 2.5 g/cm^3 . In radiowaves the reflectivity of bright regions (continents) is much lower than that of the dark ones. Comparison of reflectivity and thermal inertia (determined from infrared observations [52]) of bright regions with electrical and thermal parameters widespread on Earth, leads to the conclusion that, if the planet's surface is basically constituted of silicates as the Earth's crust, then the cover of bright regions should itself constitute a tiny sandy dust with a density of 1 g/cm^3 [53].

Some interesting deductions were made by Sagan et al [54] as a result of investigation on variations of intensity and of the spectrum of the signal reflected by Mars. They discovered that the reflection intensity maximum is observed not at the time, when the middle part of the dark regions crosses the center of the visible disk, but when the edges pass it. Moreover, it was noticed that at the approach of the dark region toward the center of the disk the center of gravity of the reflected signal's spectrum is shifted upward in frequency, while with its recess it is displaced downward (which is impossible to expect if the planet's surface has a correct spherical shape). These phenomena were interpreted as a sign that the dark regions represent elevations, which descend smoothly toward the bright regions. Although dark regions have, in principle, much greater reflectivity than the bright ones, they can produce a reverse specular reflection to Earth only in the case, when their slopes assume a perpendicular position relative to the incident ray.

The estimates performed in work [54] show that the steepness of dark regions' inclinations constitutes several degrees; besides, the greatest steepness is observed in the zones of martian canals. According to these estimates, the difference of altitudes between the dark and the bright regions may reach 1-20 km.* If the dark regions of Mars are elevations, then it is clear why their coloring is not affected after dusty storms: the settled dust is blown by the wind to much lower locations [55].

* Let us note that according to estimate by Shapiro et al [12], the radius variations on Venus do not exceed 5 km.

ABSORPTION OF RADIO WAVES IN THE ATMOSPHERES

OF VENUS AND JUPITER

The observation results of Venus' intrinsic radiation provided the basis to assume that noticeable absorption in the planet's atmosphere may take place only in waves shorter than 1.5 - 2 cm [38]. Therefore, the decrease of Venus' albedo by 10-15 times in comparison with the decimeter band, revealed during radar observations in the 3.6 and 3.8 cm waves [56, 41], was quite unexpected. Although the decrease of Venus' albedo happens very sharply, the reflection characteristics remain about the same as in much longer waves (with the exception of the region near the limb, where the intensity of reflection decreases more rapidly than in the decimeter band [41,42]). For the Moon or Mercury the decrease of albedo in the same band does not exceed 1.5 times.

In principle, the albedo decrease may be induced by both the absorption of centimeter radiowaves in the Venus atmosphere, and the decrease of reflectivity of the planet's surface itself. As is, for example, assumed in [57], the absorption in silicate dust, distributed in the atmosphere or settled on the surface, cannot be responsible for such a sharp albedo variation [58]. Moreover, in order that the reflection characteristics may be preserved, the absorbing dust layer should be evenly distributed on the surface, which is difficult to imagine in the presence of relief unevenness. Apparently, the albedo decrease is linked with the absorption of centimeter waves in carbon dioxide, of which the atmosphere of Venus consists almost entirely, as was shown by the measurements of AIS "Venera-4" [59].

In 1962, Schuster and Levy [60], have performed measurements of the rotation of the polarization's plane of Venus-reflected radiowaves, with the view of detecting the Faraday effect in the planet's ionosphere. The results of these measurements are evidence that the observed rotation in 12.5 cm wave, may be entirely ascribed to the Earth's ionosphere; they point to the absence of a noticeable magnetic field near the planet. This deduction does not contradict the direct measurements performed on AIS "Mariner-2",

which did not register any variation of the magnetic field's strength in the interplanetary space, as the station passed at the distance of 36 thousand km. from the surface of Venus [61].

The ionosphere of Venus does not contribute any noticeable distortions to the propagation conditions even in meter waves [31,32], indicating that the concentration of charged particles in the ionosphere on the dark hemisphere of Venus (the measurements in question were performed near the lower conjunction) does not exceed on the average the concentration of charged particles in the upper atmosphere of the Earth.

These conclusions were confirmed during the flight of AIS "Venera-4" and "Mariner-5". Measurements of AIS "Mariner-5" have shown, that by comparison with the Earth, Venus has a very thin ionosphere. The electron concentration on the nighttime side constitutes approximately 10^4 cm^{-3} , while on the daytime side it is $5 \cdot 10^5 \text{ cm}^{-3}$ [62].

The most remote planet, whose investigation could be realized owing to the attained sensitivity of radar installations, is Jupiter. The first radar observations of Jupiter were undertaken in USSR in 1963 in the 39 cm wave [63], and in USA in the 12.5 cm wave [64]. For a 22-hour averaging of observations in 39 cm wave, the estimate of the energy of the reflected signal constituted 1-1.5 of the RMS value of the error that could have been induced by the fluctuation noise. In observations in the 12.5 cm wave, the energy of the reflected signal was separately averaged by intervals, in the course of which the zones of 450° extension along Jupiter's longitude were passing through the center of the planetary disk. The signal was detected only in the intervals, corresponding to one of these zones, whereupon the estimate of signal energy exceeded the RMS value of the fluctuating error by a factor of 8.

The Jupiter observations were conducted in 1964, 1965 and 1966 at the Ionosphere Observatory of Aresibo in the 70 cm wave [49] with considerably higher installation sensitivity. The experiment was set in a manner conducive to as close a reproduction of the conditions of the two previous observations

as possible. The detection of the reflected signal was not achieved, although the installation's response was sufficient for its detection, provided the Jupiter's albedo in the 70 cm wave would have been even 160-200 times less than should follow from the observations in the 39 cm and 12.5 cm waves. The Jupiter observations in the 12.5 cm wave, repeated in 1964, also proved to be without results [65].

On the basis of negative results of the latest observations, conclusion is being drawn on the possible variations of reflectivity conditions on Jupiter (of which the mechanism is unknown) by comparison with 1963, or else, in the presence of unnoticed interferences in the first observations which were assumed to be the reflective signal [49]. In the second case it remains to admit that in the very deep Jupiter atmosphere radiowaves damp practically completely [55].

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N.B. Follow photographs of the recipients of the 1962 Lenin award, previously released with our ST-RA-LPS-10222, October 1964.



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AUTHORS

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ON RADAR LOCATION OF
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A.M. SHAHOVSKOY



В. П. Минашин
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