V Session: RADAR OBSERVATIONS OF THE PLANETS

A Review of Radar Studies of Planetary Surfaces

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In recent years, radar has been used to study the surfaces of the planets Mercury, Venus, Mars, and Jupiter. In the case of Venus, attenuation in the planetary atmosphere at short wavelengths has also been reported. For Mercury and Venus, where the diurnal rotation is difficult to establish by other means, radar has provided a clear-cut determination of the sidereal periods as 59 and 247 days, respectively.

Mercury is found to possess surface conditions not unlike those on the Moon. Venus appears to have a surface considerably denser and smoother than the Moon, but displaying several localized regions of scattering enhancement. Mars appears smoother than the other planets, with a marked degree of surface differentiation. Except for one brief period of observation in 1963, Jupiter appears exceedingly inefficient as a reflector of decimetric radio energy.

1. Introduction

The extension to the planets of radar techniques in use against the Moon presents a severe technical challenge. The closest and most easily detected object beyond the Moon is Venus; but even under the most ideal conditions this planet returns an echo some 5 million times weaker than does the Moon. Nevertheless, there now exist a number of facilities with sufficient sensitivity to observe not only Venus, but Mars, Mercury, and perhaps Jupiter.

Far less is known about the planets than about the Moon, and, therefore, there is potentially more value in applying radar methods to the study of planetary surfaces. The techniques are generally the same, but because of the weaker echo signal strengths more compromises with data resolution must be made. It is only in the past several years that radar information on planetary surfaces is becoming available.

Of particular importance is the extension to the planets of the range-Doppler mapping techniques developed in connection with the Moon. Since the resolution inherent in these methods depends primarily on the signal-to-noise available, and not on angular resolution, they may yield far more information on surface details of distant planets than visual observation. In the case of Venus and Jupiter, the greater penetrating power of radio wavelengths also permits investigation of surface layers inaccessible to optical observers. An immediate and obvious application of this capability is to the problem of determining rotation rates where these are poorly known because of distance or obscuration.

2. History

The first serious discussion of the possibilities and technical difficulties of using radar to explore the planets was given by Kerr [1952]. It was not until 1958, however, that sufficient radar capability became available at the Lincoln Laboratory of Massachusetts Institute of Technology to justify an attempt to observe Venus. In their report of this attempt [Price et al., 1959], success was claimed on the basis of two observations made on 10 and 12 February 1958. The signals were quite weak, however, barely exceeding 3 standard deviations of the accompanying noise, and were obtained only after extensive analysis on a digital computer. On the basis of the agreement in Doppler shift with the expected value and the self-consistency of the values obtained on the two days, it was felt that the results were genuine. A radar cross section for the planet of approximately πa^2 (with a being the planetary radius) was obtained. Measurements made at subsequent close approaches of the planet, however, have found a different value for the orbital dimension, and a very much lower value for the cross section than the earlier work. Therefore, it must be assumed that for some reason a spurious response was present which gave rise to the early results.

At the following conjunction in 1959, using much the same equipment, Price and Pettengill [1961] failed to observe echoes from Venus. Evans and Taylor [1959] working at the Jodrell Bank Experimental Station of the University of Manchester, England, reported a successful result in agreement with the 1958 measurement. Their signal was also weak, however, and they did not exclude the possibility that it might have been caused by noise alone.

By the inferior conjunction of spring, 1961, sufficient capability had become available to permit attempts to observe Venus by groups not only at the Lincoln Laboratory [Pettengill et al., 1962] and Jodrell Bank [Thomson et al., 1961], but also at the Jet Propulsion Laboratory of the California Institute of Technology [Victor and Stevens, 1961], the Radio Corporation of America [Maron et al., 1961], and in the Soviet Union [Kotelnikov et al., 1962a]. The 1961 measurements were in reasonably good agreement concerning the values of the astronomical unit which were obtained and in the cross section—approximately $0.1\pi a^2$. But the JPL and MIT results required that the planet rotate very slowly on its axis, perhaps as slowly as its

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orbital rate around the Sun, while the Russians reported observations which led to a rotational period of 10 or 11 days.

The inferior conjunction of fall, 1962, was again observed in the USSR [Kotelnikov et al., 1963a], and by JPL [Goldstein, 1964a; Carpenter, 1964]. By measuring the way in which the bandwidth of the returned signal varied with the date of observation, JPL was able to establish that the planet possessed a retrograde rotation of about 266 days. The Soviet workers were able to reproduce their results of 1961 from which they had deduced a rotation of about 10 days, but could not satisfactorily explain them. They also reported results in agreement with a retrograde rotation of about 250 days' period.

In addition, in 1962, two new groups reported observations of radio echoes from Venus. Working at 50 Mc/s, Klemperer et al., [1964] reported a cross section of approximately $0.2\pi a^2$. In common with the groups working at higher frequencies he noted that the Venusian surface slopes were significantly smoother than the Moon. A series of measurements at 38 Mc/s was also reported by James and Ingalls [1964]. They found a mean cross section of about 0.15 times the geometrical cross section but with substantial variation from day to day.

In June of 1962, radar detection of Mercury was reported in the USSR [Kotelnikov et al., 1962b], using much the same equipment and techniques as were used shortly afterward to observe Venus. The signal was not strong; however, detection seems reasonably certain. A fractional cross section of about 0.06 was obtained, which is substantially less than for Venus but comparable with the value obtained for the moon. In 1963 JPL [Carpenter and Goldstein, 1963] also reported a detection of Mercury in no severe disagreement with the earlier Russian result.

Radar measurements of Mars have been reported during the opposition of early 1963 by both JPL [Goldstein and Gillmore, 1963], and the Soviet group [Kotelnikov et al., 1963b]. Both groups of workers found a fractional cross section which varied according to the region of Mars under observation from 0.02 to over 0.10. Both are in agreement that Mars possesses a surface which at radar wavelengths is significantly flatter than that of Venus.

In the fall of 1963, Jupiter was claimed to have been observed by both the Soviet Group [Kotelnikov et al., 1964] and JPL [Goldstein, 1964b]. Since Jupiter possesses a very deep and presumably absorbing atmosphere, it might be expected that signals would not be returned at frequencies high enough to penetrate the terrestrial ionosphere. The JPL results appear to be consistent with reflection from material suspended in the upper atmosphere of Jupiter. In view of recent results from the Arecibo Ionospheric Observatory to be reported subsequently, the USSR results are in some doubt.

Considerable efforts were undertaken to observe Venus during the 1964 inferior conjunction by groups at JPL, the Arecibo Ionospheric Observatory of Cornell University, MIT, Jodrell Bank, and in the USSR. Although largely unpublished, the results of these measurements appear to confirm the earlier conclusions that Venus is smoother than the Moon and rotating with a retrograde period of about 250 days. Among the most interesting of those that have been published, however, is a report of observations made at a wavelength of 3.6 cm [Karp et al., 1964]. The low reported cross section of 0.009 and the wide spectral dispersion has been interpreted by the authors as caused, at least in part, by significant absorption in traversing the atmosphere of the planet.

3. Techniques and Relative Detectabilities

As brought out in the introduction, the planet most easily detected by radar is Venus, which at inferior conjunction (closest approach) still returns an echo 5 million times (or 67 dB) weaker than the Moon. The enormous gap in level was spanned in less than 15 years as radar systems and techniques were improved. While it seems unlikely that the next 15 years will see a corresponding further improvement, it is interesting to ask what targets would be uncovered with an additional improvement in performance. Figure 1 plots the relative signal strength to be expected from the various planets and their moons, under the assumption that they scatter like Venus. Although this assumption is now known not to be strictly true for the inner planets, and is likely to be considerably in error for the giant planets, it still serves as an approximate guide. Along the abscissa is shown the echo delay for each target. The dates shown for Mars and Mercury mark the positions for the opposition and inferior conjunction, respectively, when these occur in the months shown. Perhaps the most immediate and obvious conclusion is how large a fraction of the solar system can be covered with a further improvement equivalent to that necessary to achieve the first Venus echoes.

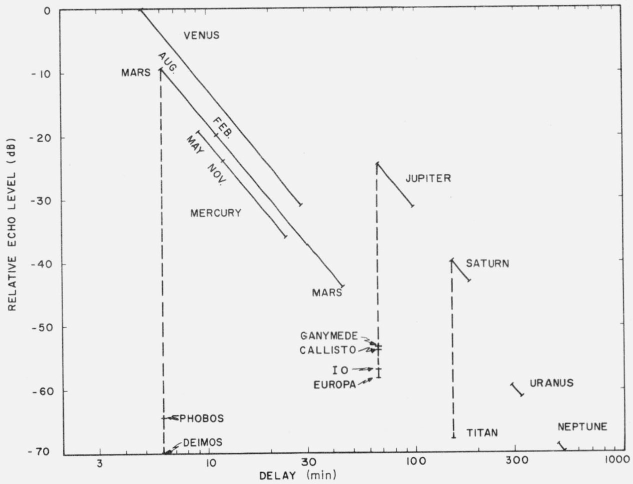

FIGURE 1. *Relative detectability and echo delay for the planets and their Moons by radar, assuming equal surface reflectivity.*
Months listed by tick marks for Mars and Mercury show detectability when closest approach occurs on that date.

Most of the increase in performance which has made radar astronomy possible has stemmed from the use of very large antennas. Since the gain of the antenna enters twice in the radar equation and is proportional to the area, performance depends on the fourth power of antenna diameter. Currently the largest antenna in regular use for the radar study of the planets is the 1000-ft diam reflector of the Arecibo Ionospheric Observatory in Puerto Rico. Average transmitted power is important; most of the facilities now in operation use between 100 and 150 kw. Finally, the excess noise temperature of the receiving system is significant since it determines the weakest signal which can be observed. Perhaps the most striking example of how low this quantity may be reduced is given by JPL [Goldstein, 1964a] which has achieved a value as low as 37 °K. By combining all these factors, MIT has achieved a level of sensitivity of 20 dB, JPL and the Soviet group approximately 25 dB, and the AIO 35 dB beyond the bare ability to detect Venus at closest approach.

In their attack on the problem of planetary detection, the various groups appear to divide into two camps. The older, represented by MIT [Pettengill et al., 1962], the early Jodrell work [Thomson et al., 1961], Jicamarca [Klemperer et al., 1964], and the AIO, send out pulses of energy having peak powers in the neighborhood of several megawatts. Pulse widths range from 100 μsec up to many milliseconds, at repetition rates such that the average power is of the order of 100 kw. More recently, JPL. [Victor and Stevens, 1961], the Soviet group [Kotelnikov et al., 1962a], El Campo [James and Ingalls, 1964], and Jodrell Bank [Ponsonby et al., 1964] have employed a CW transmission, with various forms of phase and frequency coding. In the past several years both camps have employed increasingly sophisticated modulation and detection schemes which have had the effect of leveling the relative advantages and disadvantages of the two techniques, making them both depend largely on the average power employed. Suffice it to say that the major groups in the field now have a signal delay measurement accuracy of better than 50 μsec where signal-to-noise permits, and a Doppler frequency shift measurement accuracy approaching 0.1 c/s. Systems now in existence are adequate for detecting Venus and Mercury at almost all points in their orbits, and Mars and Jupiter at close approach.

4. Planetary Surfaces

In connection with radar studies of the lunar surface (see, for example, Evans and Pettengill, [1963]) it has been shown how the intensity of the target echo could be related, at least loosely, to the type of surface material comprising the reflecting surface. Similarly for the planets, one can gain some idea of the surface conditions from the strength of the return.

Venus. For Venus, Victor et al. [1961], Pettengill et al. [1962], Carpenter [1964], Kotelnikov et al. [1963a], James and Ingalls [1964], and Klemperer et al., [1964] have found values for the fractional cross section lying between 0.1 and 0.2, with the higher values generally associated with the longer wavelengths. All the measurements indicate a significantly higher reflectivity than for the Moon. If one applies the same analysis used in the case of the Moon, one finds a surface dielectric constant of between 4 and 5. Such a value is quite consistent with a surface composed of dry rocks not unlike many rocks of the Earth's surface. The presence of significant amounts of liquid water at the surface seems to be ruled out. The low absolute value of the reflectivity and its relative independence of frequency also make a dense Venusian ionosphere appear unlikely as a source of the reflections. A variation in intensity reported by some workers [James and Ingalls, 1964] raises the possibility that differentiation of the surface may exist which effects the signal intensity as various portions of the planet rotate into the central region of the planetary disk. A measurement which falls outside this group and which has interesting implications has been reported by Karp et al., [1964]. Taken at a wavelength of 3.6 cm, their results yield a fractional cross section of only 0.009 ± 0.003, which is some 10 times less than the results at larger wavelengths. The most likely explanation seems to lie in a significant amount of absorption as the radiation traverses twice the planetary atmosphere. In this connection it is interesting to note that at wavelengths just below 3 cm, the planetary radiometric temperature falls abruptly, indicating absorption sufficient to bring the measured emission into equilibrium with the cooler upper layers of the atmosphere (see the review by Mayer, [1961]).

Several workers, [Smith, 1963; Kotelnikov et al., 1963a; and Muhleman, 1964], have reported angular scattering measurements of Venus. The Soviet results are shown in figure 2. All are in agreement that the echo possesses the same qualitative features as do lunar echoes, namely, that the bulk of the return appears to be related to coherent reflection from smooth areas of the surface near the center of the disk. In the case of Venus, however, the surface appears significantly flatter than for the Moon. Muhleman [1964] has applied an analysis similar to that developed for the Moon and derives a mean surface slope parameter some 3 times smaller than for the

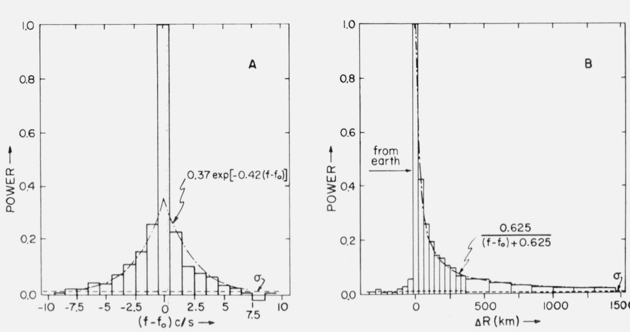

FIGURE 2. *Venus echo frequency dispersion (A) and delay dispersion (B) as observed during the fall of 1962 in the USSR by Kotelnikov et al. [1963a] at a frequency near 700 Mc/s.*
The dotted lines show the empirical fit given by the functions shown.

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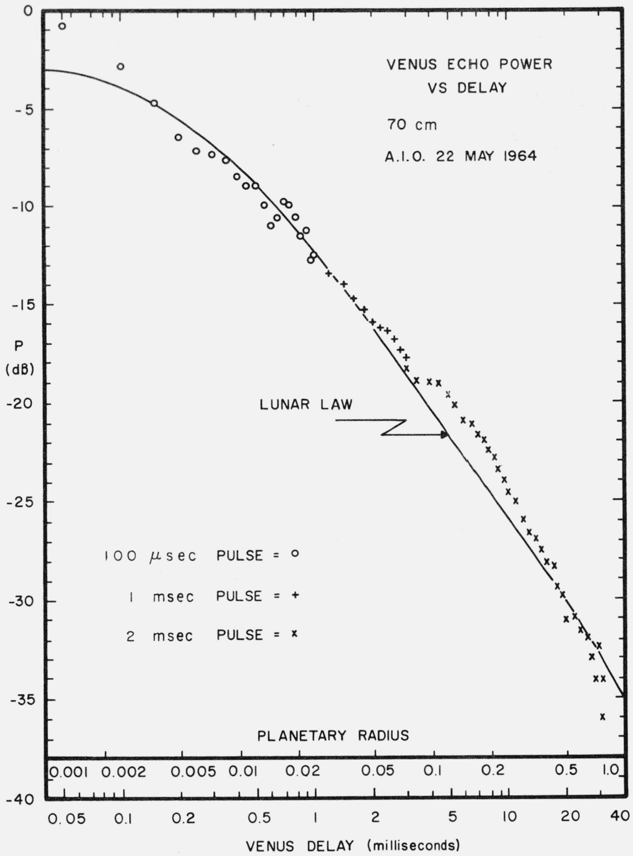

FIGURE 3. *Venus echo power versus delay observed in 1964 at 430 Mc/s at the AIO.*

The solid curve represents the corresponding behavior of the Moon, scaled to the Venus radius. Note the similarity between the two laws, holding except for the region near the center of the disk, where Venus appears smoother and more reflective than the Moon.

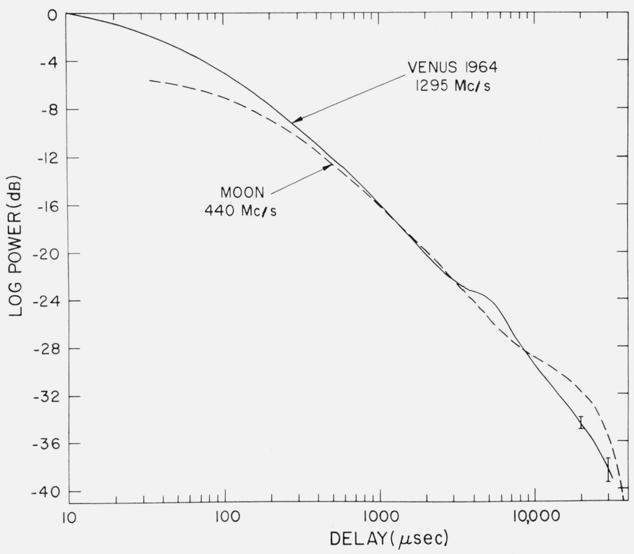

FIGURE 4. *Venus echo power versus delay observed in 1964 at 1295 Mc/s by the Millstone radar of MIT, Lincoln Laboratory [Evans, private communication].*

Again the lunar law (at 440 Mc/s) has been superimposed. Note the similarity in Venus scattering between 1295 and 430 Mc/s (fig. 3).

Moon. More recently, unpublished results from the MIT and AIO groups indicate that the Venus slopes may have more nearly one-half the average inclination found on the Moon. Figure 3 displays the scattering law obtained at 70 cm at the AIO in 1964, while figure 4 shows the results obtained at 23 cm at MIT (Evans, J. V., private communication). For comparison the lunar scattering laws obtained under similar conditions are also plotted. Again it will be noted that the initial decay of power with range is less than for the Moon, indicating a smoother planetary surface. It is interesting that, at least on the basis of these two sets of measurements, there appears to be little dependence on frequency of the angular scattering laws of Venus as compared to those of the Moon. Also of interest is the presence of a rough scattering component for Venus at greater delays, not departing too greatly from the lunar law.

Mercury. For Mercury the available information is much more primitive. The USSR [Kotelnikov, 1962b], JPL [Carpenter and Goldstein, 1963] and the AIO [Dyce et al., 1964] are in good agreement that the surface reflectivity is close to 0.06, similar to the value obtained for the Moon. The scattering law for Mercury is currently poorly determined. The recent finding at the AIO [Pettengill and Dyce, 1965] that the rotation rate is about 50 percent faster reduces the roughness required to explain their measured frequency dispersion. Preliminary pulse measurements made at the AIO are compatible with a scattering law similar to that observed for the Moon. In view of the common environment faced by both these objects, a conclusion of similarity seems reasonable.

Mars. For Mars, the best measurements until very recently were those of JPL [Goldstein and Gillmore, 1963], who have measured the radar cross section as a function of the target longitude facing the radar. Their results are shown in figure 5, where an enhancement of reflectivity in the region of Syrtis Major may be seen. The USSR results [Kotelnikov et al., 1963b] appear to be sufficiently weak to have significance only when all longitudes are added together. Their finding of an extremely narrow spectral component is interesting but has not yet been verified by other workers. The low average cross section reported by both groups (0.03 by JPL and 0.07 in the USSR) is difficult to explain. The recent radar observations of Mars at the AIO, using a wavelength of 70 cm, are not yet fully reduced but appear to yield reflectivities varying from 0.03 to 0.12. Particularly interesting is the presence of both a stable, broadband frequency component and a variable narrowband component associated with specific longitudes. A correlation of enhanced reflectivity with the region of Trivium Charontis is reported [Pettengill and Dyce, 1965].

There are several possible sources for the wide degree of fluctuation found in the echoes from Mars. If the planet were largely composed of porous material, in the manner of the lunar surface but even more porous, the low mean reflectivity could be explained.

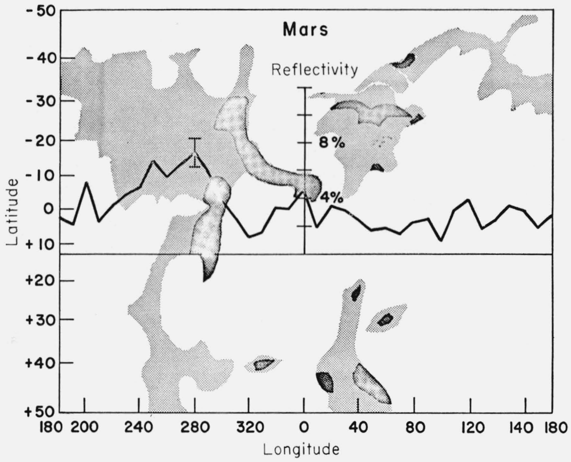

FIGURE 5. *The radar reflectivity of Mars at a frequency of 2388 Mc/s plotted versus planetary longitude* [*Goldstein and Gillmore, 1963*].
Note the apparent correlation between high reflectivity and the region of Syrtis Major.

A distribution of surface slopes not unlike that found on the Moon would suffice. Suppose now, however, that unlike the Moon there existed certain regions of unusual smoothness (low areas with sedimentation?) which would occasionally move under the radar beam. When properly alined normal to the incident energy, these facets would be very effective in returning energy and would give rise to an enhancement in the total power even if the intrinsic specific reflectivity remained low. The reflectivity need not be low, however, and one may manufacture many models from marshes to salt flats which would all be compatible with the observed enhancement and relatively narrow spectral characteristics.

Jupiter. As a radar target, Jupiter is extremely puzzling. All models proposed for this planet call for an extremely thick and dense atmosphere. Even if a true surface exists, it is impossible to visualize a penetration by radiowaves to this surface which would survive extinction by absorption. Thus only reflection by solid or liquid matter of sufficient size suspended in the upper layers of the atmosphere, or reflection by an ionospheric plasma, would seem able to return measurable power.

Despite the unlikelihood of an efficient reflection mechanism at wavelengths in the decimeter to meter range, groups at JPL [Goldstein, 1964b] and in the USSR [Kotelnikov et al., 1964] have reported successful measurements in the fall of 1963 which require specific reflection efficiencies of 0.6 and 0.1 respectively. The statistical significance of the latter measurement is not high, however, since the reported output signal-to-noise ratio is only 1.3.

The JPL measurements cannot be dismissed on the same gounds, however, since the best case exhibited an output signal-to-noise ratio of about 8. Positive detection was obtained over only a small region in planetary longitude and was well correlated only with the System I coordinates, indicating a source moving with the outermost (visible) atmospheric circulation. The spectral width of the echo was narrow, indicating a high degree of smoothness of the scattering medium. The source, therefore, may have been (but is not required to be) narrow in latitudinal extent. The high intrinsic reflection efficiency, however, requires that the scattering surface extend through nearly the entire longitude region (about 45°) corresponding to the integration time of the successful observations.

In the fall of 1964, radar observations of Jupiter were carried out at the AIO at a wavelength of 70 cm [Pettengill and Dyce, 1965]. Despite a greatly increased system sensitivity as compared to the earlier measurements, no significant detection was obtained. By summing over all longitudes of the planet in a bandwidth of approximately 100 c/s, to simulate the results reported in the USSR, the AIO group was able to place an upper limit on the specific reflectivity of 0.00045, or 200 times less than the earlier result reported at 43 cm. By summing over regions of longitude in a bandwidth of 700 c/s to simulate the measurements reported by JPL, an upper limit of 0.0036 for the specific reflectivity was obtained, a result 160 times less than that reported earlier at 12.5 cm.

It is interesting to note that if the reflection mechanism behind the JPL observation is associated with suspended particulate matter, and if this has dimensions on the order of 10 cm or less, then by the law of Rayleigh scattering there need not have been any detectable energy (i.e., which exceeded the level set by the 70-cm observations). Meteorological differences between the years 1963 and 1964 are also sufficient to explain the discordant results.

5. Planetary Rotation

The application of pulse-coherent analysis to detailed radar mapping of the surface of the Moon has been described [Pettengill and Henry, 1962]. In reducing the measurements to actual positions on the surface of the Moon, it was necessary to use the known rates of libration of the lunar surface with respect to the observer. However, by turning the process around, it would have been possible to obtain the apparent rotation of the Moon from the radar measurements to a high degree of accuracy. For Venus, where the rotation is essentially unknown from visual measurements because of the extensive cloud cover, and for Mercury, where visual observation is difficult because of the proximity of the Sun, extreme interest attaches to radar measurements.

If only frequency spectrum measurements are available, it is possible to deduce the apparent instantaneous angular velocity from the maximum extent of the spectrum, provided sufficient signal-to-noise ratio is available to ensure that one is actually observing echo power from the limbs of the planet. Of course, one must assume that the radius of the planet is known. Working within these limitations Carpenter [1964] has calculated that the rotation of Venus has a sidereal period of approximately 266 days in the retrograde sense with an orientation approximately perpendicular to the plane of its orbit. The earlier Russian result [Kotelnikov, 1962a], that the rotational period was as rapid as 11 days, appears to be discredited.

An even more powerful attack is possible if one can obtain frequency spectra at a selected and known range. As shown in Pettengill and Henry [1962], the spectra in such a case are sharply defined and avoid the necessity of assuming that echo power is being returned from the actual planetary limb. Using this technique, Goldstein [1964] has obtained from the 1962 observations a retrograde rotation of 248 days, again with an axis orientation very close to perpendicular to the orbital plane of Venus. Unpublished data from the 1964 conjunction taken at the Arecibo Ionospheric Observatory confirm this latter measurement and yield a value for the sidereal rotation of 247 ± 5 days retrograde with an axis orientation approximately 6° off perpendicularity to the orbital plane. Twenty-one measurements, reduced to the equivalent limb-to-limb Doppler spread are shown in figure 6, together with the curve which is the least-mean-squares fit to the data. The three parameters which yield the best fit curve are also shown. From the extreme accuracy with which the 21 observed points may be made to fit a theoretical curve of 3 deg of freedom, it must be concluded with no reservation that we are observing, at least at 70 cm, the actual surface of a solid, rotating body. We must not rule out the possibility, however, that there are also weaker reflections from a variable and turbulent atmosphere which can give rise to a much broader spectral component, and which may become important at short wavelengths.

For Mercury, the corresponding measurements are more difficult because of the relative weakness of the echoes. Nevertheless, Pettengill and Dyce [1965] have recently reported radar measurements which indicate that Mercury is rotating in a direct sense with a sidereal period of 59 ± 5 days. The data are summarized in figure 7. The direction of the pole is not well-determined from these limited data, but is approximately normal to the planetary orbit.

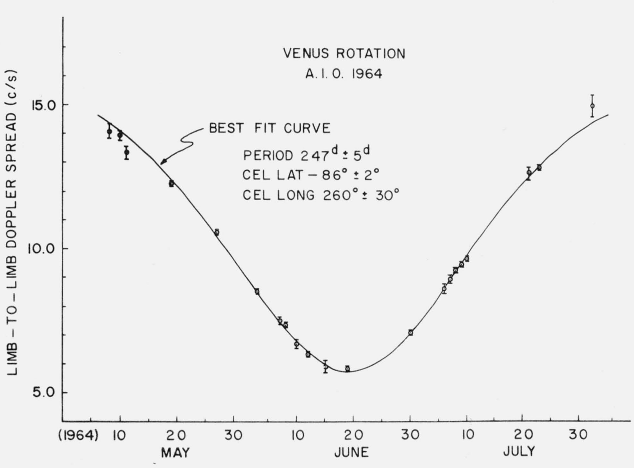

FIGURE 6. *Plot of limb-to-limb Doppler spread versus date observed for Venus during the 1964 inferior conjunction.*

The solid curve represents the least-mean-squares fit to the data and corresponds to the rotation axis specified. Data taken at the Arecibo Ionospheric Observatory.

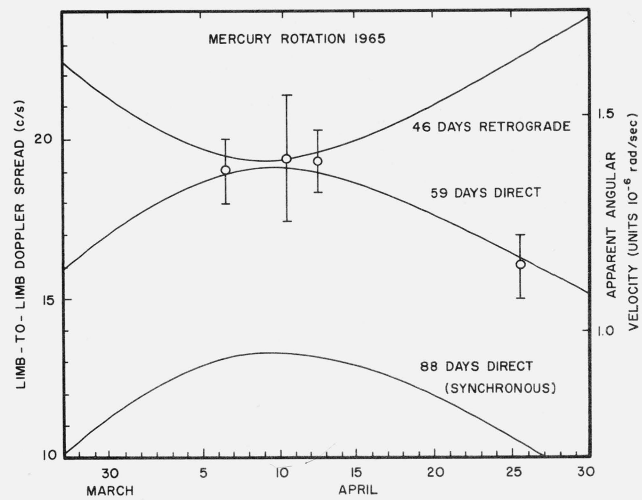

FIGURE 7. *Plot of the apparent rotational angular velocity of the planet Mercury versus data for several values of rotation during the inferior conjunction of April, 1965.*

The values inferred from the measurements are shown with their estimated errors.

The finding of a value for the rotational period of Mercury which differs from the orbital period is unexpected and has interesting theoretical implications. It indicates that either the planet has not been in its present orbit for the full period of geologic time or that the tidal forces acting to slow the initial rotation have not been correctly treated previously.

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Preliminary Venus Radar Results [1]

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1. Introduction

This note presents some of the preliminary results obtained by the Jet Propulsion Laboratory during its radar observations of Venus. These experiments were performed during the months surrounding the inferior conjunction of June, 1964.

The radar parameters were as follows:

Power = 100 kW
Frequency = 2388 Mc/s
Antenna Gain = 108.5 dB (two-way)
System Temperature = 33 °K.

Several different types of experiments were performed, but here we shall report on only spectrum and range-spectrum analysis of the echo. Each planetary reflecting element has four attributes which may be isolated by the radar: velocity, time delay, intensity for normal, and intensity for crossed polarization. The methods used to isolate these attributes are described by Goldstein [1964].[2]

2. The Rotation of Venus

Figure 1 presents the contours of constant time delay and of constant velocity (or Doppler frequency shift).

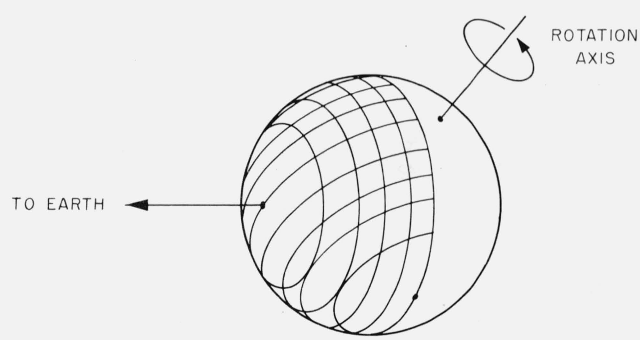

FIGURE 1. *Countors of constant time delay and of constant frequency shift.*

The time-delay increments are 125 μsec (11 miles) and are constant. The frequency increments are not constant, but are proportional to that rotation component which is perpendicular to the line of sight. As Venus passes the Earth in its orbit, the frequency increments first decrease and then increase. This phenomonon enables the three components of Venus's rotation vector to be determined. Goldstein [1964] gives the details of this computation.

A sample of the basic data obtained is given in figure 2. The echo arising from each ring of constant time delay has first been separated by the radar and then spread into its frequency components in order

[1] This paper presents the results of one phase of research carried out at the Jet Propulsion Laboratory, California Institute of Technology, under Contract No. NAS 7-100, sponsored by the National Aeronautics and Space Administration.

[2] Goldstein, R. M. (1964), Venus characteristics by earth-based radar, Astron. J. **69,** No. 1, 12–18.