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Radar Determination of the Rotations of Venus and Mercury

R. B. Dyce and G. H. Pettengill*

Cornell–Sydney University Astronomy Center, Arecibo Ionospheric Observatory,† Arecibo, Puerto Rico

and

I. I. Shapiro

Lincoln Laboratory,‡ Massachusetts Institute of Technology, Lexington, Massachusetts

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By measuring the frequency dispersion of time-gated radar echoes from Venus and Mercury at the Arecibo Ionospheric Observatory, the apparent rotation rates of these planets have been unambiguously determined. The combination of many such measurements made over a period of time has permitted a separation of the intrinsic rotation from the contribution of the relative orbital motion of the earth and the target planet. From observations over a three-month period surrounding the inferior conjunction of 1964, we find that Venus has a solar rotation period (i.e., with respect to the planet–sun line) of 117±1 days and a sidereal rotation period of 245.1±2 days (retrograde); its rotation axis has a declination of −66.7±1 deg and a right ascension of 90.3±1 deg (1950.0). The inclination of the axis is −89.8±1 deg with respect to the ecliptic and −86.7±1 deg with respect to the orbital plane of Venus. These results are consistent with Venus making four complete axial rotations as seen by an earth-based observer between inferior conjunctions. For such a retrograde rotation a sidereal period of 243.16 days is required. Data obtained near the inferior conjunctions of Mercury in April and August 1965 indicate that the axial rotation of Mercury is direct and has an average solar period of 176±9 days and a sidereal period of 59±3 days. The direction of the rotation axis, although not well determined by these data, seems to be inclined to the normal to Mercury's orbital plane by less than 28°. These results are consistent with Mercury's axial rotation being locked to its orbital motion such that the sidereal period of the former is exactly two-thirds of that of the latter.

Enhanced scattering from distinct parts of the Venus surface have also been detected and a corresponding contour map of the surface radar reflectivity is presented.

I. INTRODUCTION

Optical observations have not provided useful information on the rotation of Venus because the surface is always hidden behind a largely opaque and featureless cloud cover. The only reliable quantitative determinations of the direction and rate of rotation of Venus have resulted from radar measurements. The first successful Venus radar experiments, conducted in 1961 by the Jet Propulsion Laboratory (Victor and Stevens 1961) and by MIT Lincoln Laboratory (Staff, Millstone Hill Radar 1961), indicated that the rotation period was very long, but were not accurate enough to determine the sense of rotation. Smith (1963) did, however, note the possibility of retrograde rotation.

More sensitive radar observations of Venus performed at JPL in 1962 resulted in two separate determinations of the rotation rate. One (Carpenter 1964) was based on following from day to day the spectral position of a "feature" on the surface of Venus; the other (Goldstein 1964; Carpenter 1964) made use of frequency dispersion techniques. The results were consistent and showed the rotation to be retrograde with a period of about 250±40 days and an axis nearly normal to the ecliptic. Although omitting details, Kotelnikov *et al.* (1963) also reported a retrograde rotation with a period between 200 and 300 days, based on their 1962 measurements.

The 1964 measurements at JPL were consistent with the rotation rate results obtained there in 1962 but were considerably more accurate; Goldstein (1965) reported a period of 250±9 days with the axis direction having a declination $\delta=-62\pm4$ deg and a right ascension $\alpha=81\pm6$ deg. Carpenter (1966) concluded that the period lay between 244 and 254 days with the direction of the axis having coordinates: $\delta=-68\pm4$ deg and $\alpha=75(+10, -4)$ deg. Measurements made at Jodrell Bank in 1964 also confirmed the retrograde aspect of the rotation and yielded a rotation period between 100 and 300 days (Ponsonby *et al.* 1964). Similarly, the 1964 Lincoln Laboratory spectral measurements are consistent with a retrograde rotation of Venus (Evans *et al.* 1965). The 1964 radar measurements of Venus made at the Arecibo Ionospheric Observatory of Cornell University, which are reported here in detail, were presented in preliminary form by one of us (Shapiro 1964) to the International Astronomical Union. The more refined results indicate a rotation period of 245.1±2 days with the axis having a declination of −66.7±1 deg and a right ascension of 90.3±1 deg (mean equinox and equator of 1950.0), in reasonably good agreement with the JPL results.

The planet Mercury is not encumbered with a veil of clouds, as is Venus, and optical observations have been carried out from the early 19th century. The first sustained observations by Schröter were analyzed by Bessel (1813), who claimed that the rotational period

* Now at MIT Lincoln Laboratory, Lexington, Massachusetts.

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was in the vicinity of 24 h. Later, however, Schiaparelli (1889) concluded from his extensive observations that Mercury was rotating slowly with a period most likely synchronous with its orbital period of approximately 88 days. Antoniadi (1934), Dollfus (1953) and others also found the period of rotation to be 88 days from analyzing their visual and photographic observations.

Early radar measurements by Carpenter and Goldstein (1963) seemed to confirm the 88-day rotational period. These measurements, however, were based on spectra integrated over all ranges, and, in view of the limited signal-to-noise ratio were possibly subject to considerable systematic error in interpretation. The 1965 radar measurements of Mercury, discussed below in detail, indicate that its rotation is direct with a period of 59 ± 3 days. (A preliminary report, based on some of these data, was published previously by Pettengill and Dyce 1965.)

After the disclosure that Mercury's axial period was substantially shorter than its orbital period, several groups undertook a re-examination of the optical measurements (McGovern, Gross, and Rasool 1965; Colombo and Shapiro 1965). Except for some of Schiaparelli's data, all groups of optical observations published had been made at intervals separated by very nearly even multiples of Mercury's orbital period and hence were unable to distinguish between a rotation value of 88 days and the new radar-determined value of 59 days (i.e., two-thirds of the orbital period), as pointed out by Colombo and Shapiro (1965). More recently Dollfus (1966) has revealed that some previously unpublished optical observations are definitely inconsistent with an 88-day rotation period but are consistent with 59 days, apparently confirming the radar value.

II. THEORY OF ROTATION DETERMINATION

Before discussing the data reduction in detail we review briefly the fundamental principles involved in the radar determination of planetary rotations. The mathematical theory is given by Shapiro (1967).

Most of the echo energy returned by a planet to the observing radar results from quasi-specular reflection from areas on the planet that are perpendicular to the incident radar waves. For a smooth sphere these areas are located near the intersection with the planetary surface of the line joining the radar site and the center of the planet. (This intersection is commonly called the subradar point on the target.) The rough elements on the surface, which are comparable in size to the illuminating wavelength, give rise to weaker but detectable echoes at greater delays because of their contribution to the energy that is scattered back in the direction of the radar even at positions where the mean surface of the planet is not normal to the direction of incidence. Each element of area on the surface will, therefore, return an echo characterized by a particular value of time delay and also by a particular value of Doppler frequency shift, the latter depending on the component of velocity of the element along the direction of propagation of the incident wave. These facts underlie the fundamental principle of delay–Doppler (often called "range–Doppler") mapping (Green 1960).

This principle may, perhaps, be pictured more clearly by considering a very short radar pulse reflected from a distant, rotating planet. At any particular instant slightly later than its time of arrival at the subradar point on the planet, the pulse illuminates a particular annular region centered on the subradar point. Reflections from each such annulus, or ring, are, therefore, associated with a particular value of time delay. To determine the association between Doppler shifts and surface points, we note that for a rigid target all surface points that lie in a plane parallel to both the target's apparent axis of rotation (see below) and the radar line of sight have the same component of velocity in the direction of the radar. Each strip where such a plane intersects the target's surface is, therefore, associated with a unique Doppler shift. Furthermore, the difference between the Doppler shift associated with the subradar point and that which characterizes each strip is proportional to the plane's displacement from the target's center. By combining these two ways of associating points on the surface of the target with energy received at a particular time delay and with a particular Doppler shift, we can produce a delay–Doppler map of the surface. This technique was employed in the work described in the following sections.

A twofold ambiguity in mapping from delay–Doppler coordinates on to the actual surface exists because pairs of points symmetrically placed with respect to the target's apparent equator have identical delay and Doppler coordinates. For this reason, along the equator the Jacobian of the transformation from usual surface coordinates to delay–Doppler coordinates is singular. This peculiarity proves to be of enormous benefit for the application to the rotation rate determinations: The power associated with the instantaneous backscattered reflections from a given annulus will be greatest (as will the signal-to-noise ratio) at the maximum and minimum frequencies represented since these correspond to the two regions (on the apparent equator of the target) where the Doppler strip and the delay annulus are tangent to each other, and, therefore, enclose the greatest surface area within the bounds of the given delay–Doppler resolution. The bandwidth (i.e., the difference between the values of the maximum and minimum frequencies represented) is directly proportional to the rate of rotation of the planet as seen from the radar. This apparent angular velocity of rotation is composed of two parts: (1) the contribution of the intrinsic, or sidereal, rotation of the planet, and (2) the contribution attributable to the relative motion of the radar site and the center of the planet. The bandwidth is thus proportional to the projection on a plane perpendicular to the radar line-of-sight of the vector sum of the intrinsic angular velocity of rotation of the planet and the angular velocity associated with the relative orbital motion. As the orbital positions change, not only does the relative orbital angular velocity vector change, but the vector sum of it and the intrinsic angular velocity is projected on a plane of differing orientation. By making a series of bandwidth measurements from different relative orbital positions, all ambiguities are resolvable (in principle, at least) and all three scalar parameters associated with the axial rotation of the planet can be estimated by using the method of weighted-least-squares.

III. RADAR CHARACTERISTICS AND METHOD OF DATA REDUCTION

The radar observations to be discussed were made with the 1000-ft diameter antenna and associated equipment located at Arecibo, Puerto Rico. Characteristics of the radar are given in Table I. During each observation the antenna beam is continuously directed toward the apparent position of the planet for a period of time permitted by the 20-deg zenith angle limit of the antenna design. A train of rf pulses (derived from a continuously running master oscillator) is radiated for a time period slightly exceeding the round-trip time delay. The transmitter is then turned off and the receiver system turned on after a delay of about 30 sec. The receiver timing and sampling pulses are generated in a manner that removes essentially all effects of the changes in position between the earth and target planet during the course of the observation. A provisional ephemeris is used for this purpose. A local oscillator, set at the start of the receiving period, approximately compensates for the planetary Doppler shift. (All oscillators have frequencies derived from a single master oscillator.) But, during an observation, the Doppler shift of the echo changes at a rate of about -5 cps/min, principally due to the motion of the radar site as the earth rotates. Compensation for this change is accomplished in the computer during post-run analysis by shifting the frequency ordinate according to the provisional ephemeris. A more complete description of the data-taking procedures is given in the companion paper by Pettengill, Dyce, and Campbell (1967).

Digital recording of the returned echo follows conversion to video frequencies in two parallel channels in phase quadrature (which, therefore, preserves both amplitude and phase information) and permits analysis to be made at a later time with no loss of information or accuracy yet with considerable flexibility in the manner of processing. An element of the spectrum is determined by cross correlating successive samples of the echo (corresponding to a constant relative delay on the planet) against a unit vector varying at a specified frequency. This analyzing frequency is changed in a precise manner during the course of the correlation in order to compensate the residual Doppler shift remaining in the recorded signals according to the provisional ephemeris. For Venus and Mercury, spectral aliasing was avoided by operating with a transmitted pulse repetition frequency larger than the maximum dispersion of the Doppler frequency spectrum. Thus, successive data samples corresponding to the same delay are sufficiently closely spaced to preserve unambiguously all possible information concerning the echo spectrum. The frequency resolution is proportional to the inverse of the time occupied by the pulses which are processed coherently (i.e., the number of pulses so processed times the interval between transmitter pulses). A single spectrum obtained in this way, of course, leads to a large statistical uncertainty in the determination of mean power. Many successive spectra must, therefore, be summed in the computer before a statistically significant result is obtained. This method of obtaining detailed frequency spectra while preserving delay resolution has been described previously (Pettengill 1960) and applied to echoes from the moon (Pettengill and Henry 1962).

TABLE I. Characteristics of the Arecibo Planetary Radar.

Location	18°20′46″ N geod. lat., 66°45′11″ W long., height above MSL = 364 m
Antenna diameter	1000 ft (304.8 m)
Gain	56.25 dB in zenith
Beamwidth	9 min of arc between half-power points
Sky coverage	Within 20° of zenith (approx $\delta=-1°$ to $\delta=+38°$)
Transmitted frequency	430.0 MHz (λ = 0.70 m)
Typical peak power	2.0 MW
Typical average power	100 kw
Pulse width	1.0 msec (for Venus), 0.5 and 0.1 msec (for Mercury)
First-stage receiver amplifier	Zenith Adler tube (1964); Uncooled varactor parametric amplifier pumped at 6 GHz (1965)
System temperature	About 400°K (1964); 220±40°K (1965)
Transmitted polarization	Right circular
Received polarization	Left circular

We discuss first the detailed reduction of the Venus data. For the run (defined as a complete transmission and reception interval, approximately equal to twice the echo round-trip time) which displays the best signal-to-noise ratio of each observation day, several delays are selected. These are separated by at least one-half pulse width, and lie at least four pulse widths in delay (10% of the planetary depth) from the "leading edge" of the echo. By concentrating on the spectra at greater delays, we avoid the necessity for large corrections arising from a rapid change of bandwidth with delay which smears the edges of spectra from near the

TABLE II. AIO bandwidth data from 1964 Venus radar measurements.

Date (1964)	Time (UT) h	m	s	Delay from subradar point (msec)	Bandwidth (cps)	Est. measurement error (cps)
8 May	19	00	35.0	3.95	6.00	0.13
				4.45	6.90	0.22
				4.95	7.10	0.20
				4.95	7.00	0.30
				5.45	7.16	0.20
				5.95	7.50	0.09
10 May	19	03	00.0	3.98	6.10	0.18
				4.48	6.45	0.22
				4.48	6.37	0.25
				4.98	6.94	0.08
				5.48	7.20	0.12
				5.98	7.29	0.13
				6.48	7.88	0.14
11 May	19	06	35.0	3.01	5.32	0.07
				3.51	5.60	0.12
				3.11	5.23	0.11
				3.51	5.50	0.18
19 May	18	49	00.0	4.03	5.35	0.16
				4.53	5.80	0.16
				5.03	6.08	0.13
				5.53	6.31	0.12
				6.03	6.54	0.11
				6.53	6.77	0.17
				7.03	7.00	0.16
				7.73	7.33	0.08
27 May	18	51	00.0	4.01	4.58	0.21
				4.51	4.88	0.09
				5.01	5.08	0.10
				5.51	5.30	0.14
				6.01	5.55	0.08
				6.51	5.79	0.12
				7.01	6.00	0.16
				7.41	6.10	0.16
3 June	18	33	15.0	4.02	3.77	0.10
				4.52	4.03	0.08
				5.02	4.12	0.11
				5.52	4.34	0.10
				6.02	4.52	0.16
				6.52	4.73	0.14
				7.02	4.93	0.12
7 June	17	56	00.0	4.14	3.36	0.09
				4.64	3.60	0.09
				5.14	3.75	0.11
				5.64	3.85	0.09
				6.14	3.96	0.10
				6.64	4.09	0.09
8 June	18	41	00.0	4.03	3.18	0.07
				4.53	3.37	0.08
				5.03	3.55	0.11
				5.53	3.74	0.10
				6.03	3.83	0.16
				6.53	3.94	0.08
10 June	17	12	00.0	3.47	2.74	0.06
				3.97	2.91	0.11
				4.47	3.16	0.09
				4.97	3.30	0.11
				5.57	3.45	0.16
				5.97	3.68	0.12
				6.57	3.76	0.11
15 June	17	34	00.0	3.95	2.58	0.11
				4.45	2.72	0.06
				4.95	2.88	0.04
				5.45	2.99	0.11
				5.95	3.12	0.12
				6.45	3.24	0.14
19 June	16	21	00.0	5.16	2.81	0.12
				5.66	2.95	0.17
				6.16	3.04	0.14
				6.66	3.17	0.13
				7.16	3.35	0.21
				7.66	3.27	0.20
				8.16	3.41	0.16
				10.66	4.05	0.20
				12.16	4.25	0.20
				13.66	4.34	0.14
				14.16	4.51	0.20
30 June	14	53	00.0	3.98	3.10	0.06
				4.98	3.45	0.06
				5.98	3.76	0.12
				6.98	4.09	0.06
				8.98	4.53	0.07
				9.98	4.67	0.05
				10.98	4.82	0.13
				11.98	5.10	0.06
				13.68	5.31	0.06
6 July	15	02	10.0	4.09	3.80	0.08
				4.59	4.08	0.09
				5.09	4.24	0.11
				5.59	4.49	0.08
				6.09	4.57	0.12
				6.59	4.76	0.08
				7.09	4.83	0.08
				7.59	5.13	0.11
				8.09	5.22	0.14
				8.59	5.46	0.12
				9.09	5.58	0.20
				9.59	5.61	0.09
				10.09	5.88	0.08
7 July	15	12	00.0	3.77	3.80	0.08
				4.27	3.95	0.08
				4.77	4.25	0.08
				5.27	4.45	0.08
				5.77	4.66	0.11
				6.27	4.81	0.13
				6.77	4.90	0.11
				7.27	5.11	0.08
				7.77	5.29	0.08
				8.27	5.36	0.08
				8.77	5.59	0.11
				9.27	5.74	0.08
				9.77	5.80	0.27
				10.27	5.83	0.20
				10.77	6.03	0.20
				11.27	6.24	0.20
				11.77	6.17	0.09
				12.27	6.50	0.18
				12.77	6.53	0.10
				13.27	6.57	0.10
8 July	13	48	00.0	3.77	3.93	0.11
				4.27	4.09	0.08
				4.77	4.30	0.16
				5.27	4.43	0.08
				5.77	4.74	0.18

TABLE II (*continued*)

Date (1964)	Time (UT) h m s	Delay from subradar point (msec)	Band-width (cps)	Est. measurement error (cps)
8 July	13 48 00.0			
		6.27	4.83	0.12
		6.77	5.12	0.17
		7.27	5.26	0.21
		7.77	5.40	0.11
		8.27	5.60	0.10
		8.77	5.77	0.22
		9.27	5.91	0.11
9 July	17 37 30.5	3.84	4.05	0.16
		4.34	4.17	0.12
		4.84	4.50	0.12
		5.34	4.70	0.11
		5.84	4.90	0.09
		6.34	5.05	0.09
		6.84	5.20	0.19
		7.34	5.46	0.40
		7.84	5.60	0.14
		8.34	5.76	0.20
		8.84	5.86	0.20
21 July	14 08 00.0	2.00	3.85	0.18
		2.50	4.30	0.22
		3.00	4.60	0.21
		3.50	4.80	0.20
		4.00	5.24	0.16
		4.50	5.44	0.30
23 July	13 34 00.0	3.99	5.50	0.14
		4.49	5.80	0.22
		4.99	6.15	0.15
		5.49	6.40	0.18
		5.99	6.82	0.18
		6.49	7.00	0.12
		6.99	7.20	0.13
		7.49	7.60	0.21
		7.99	7.70	0.20
		8.49	7.80	0.10
		9.49	8.20	0.20

subradar point. Samples for a given delay from successive pulses are then digitally analyzed to obtain a frequency spectrum as described above. The computer synthesizes an analyzing filter bandwidth (typically between 0.08 and 0.35 cps) that will match the frequency smearing associated with the delay resolution of the 1 msec transmitted pulse width at the various observed depths into the planet. The frequency separation between the two extreme spectral peaks (or wings) is measured from the spectral plots. A maximum limit of about 14 msec delay (or 35% of the planet's radius) is generally set by the weakening of the echo as the surface of the planet becomes less perpendicular to the radar line of sight. The limb-to-limb Doppler bandwidth for each selected delay on a given day is tested for error by computing for each the equivalent limb-to-limb bandwidth and comparing the results. This conversion is easily made by multiplying the bandwidth by the factor $a/(2a-1)^{\frac{1}{2}}$, where $a=\rho/150t$, ρ is the radius of the planet (in kilometers), and t is the round-trip delay (in milliseconds) for a radar wave traveling from the subradar point to the annulus whose associated bandwidth is being converted. The agreement is generally good, the errors being on the order of a few percent. The precision is chiefly limited by the fact that the scattering behavior of the Venus surface is nonuniform.

Even in the most favorable situations, the relatively weak echoes from Mercury permitted a determination of the spectral dispersion at delays only up to 4 pulse widths from the leading edge of the echo. To produce these spectra, analyzing filters with bandwidths of 0.5 and 1.0 cps were employed. In most other respects, the treatment of the data obtained from Mercury was similar to that for the Venus data. Of course, the errors associated with measurement were larger; nevertheless, it was possible to compare the inferred limb-to-limb Doppler bandwidths obtained at several delays and to gain some confidence from their consistency.

IV. VENUS OBSERVATIONS

The bandwidth data for Venus accumulated at Arecibo from May through July 1964 are presented in Table II. From these data, a weighted-least-squares estimate of the components of Venus' angular velocity vector was made, using the technique discussed by Shapiro (1967).

A comparison between the measured bandwidths and the values corresponding to the "best-fit" are shown in Fig. 1. The rotation period for this solution is 245.1±0.7 days, while the direction of the rotation axis has $\delta=-66.7\pm0.4$ deg and $\alpha=90.3\pm0.6$ deg (referred to the mean equinox and equator of 1950.0). The axis is almost normal to the ecliptic having an inclination to this plane of -89.8 ± 0.4 deg. The corresponding inclination to the orbital plane of Venus is -86.7 ± 0.4 deg. The errors quoted here are the standard deviations obtained formally from the covariance matrix that follows from the measurement error standard deviations given in Table II. Since a known, although small, source of systematic error [i.e., the convolutional effects of the finite pulse length and the receiver filter characteristics (Shapiro 1967)] was not included, we consider it prudent to increase the error associated with the period to 2 days and those associated with the angle determinations to about 1 deg.

Our result for the rotation period is close to the value of 243.16 days for which Venus would make on average four complete revolutions between inferior conjunctions as seen by an earth-based observer. We therefore computed the residuals based on this value and found them to be clearly larger than those shown in Fig. 1, although the differences, as intimated above, may not be significant.

The presentation in Fig. 1 does not exhibit the time variation of the bandwidths caused by the relative orbital motion of the radar site and Venus. Therefore we show in Fig. 2, as a function of date, the extrapolations of the measured bandwidths to ones that would

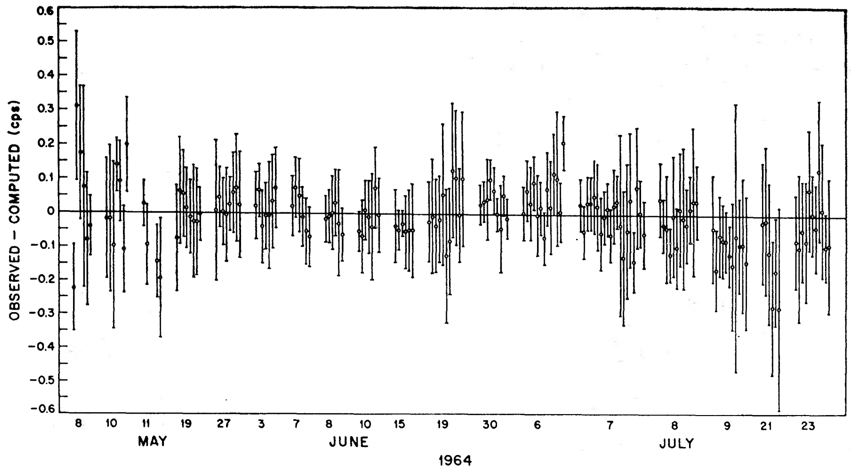

Fig. 1. Residuals obtained from the best fit of a theoretical calculation of the effects of Venus' rotation to the data of Table II. The measurements of a given day are ordered in increasing delay from left to right. The rotation of Venus corresponding to the best fit has a sidereal period of 245.1 days (retrograde) and an axis direction of −66.7 deg declination, 90.3 deg right ascension (mean equinox and equator of 1950.0).

have been measured had each of the annuli been at the limb of Venus. The corresponding best-fit curve is also included. The dip near inferior conjunction implies that the contribution to the apparent angular velocity arising from the relative orbital motions of earth and Venus must be opposing that of the sidereal spin angular velocity of Venus and indicates clearly that Venus is rotating in a retrograde direction.

The theoretical model used in the above analyses assumed the radius ρ of Venus to be 6089 km (de Vaucouleurs and Menzel 1960), and all motions were considered, including the movement of the radar site with respect to the center of the earth. Any error in ρ does not affect the result greatly since the result depends essentially only on the square root of ρ. Of course, ρ can also be estimated from the bandwidth data; a preliminary attempt indicated that the error would exceed 200 km, and hence the estimate would not be useful.

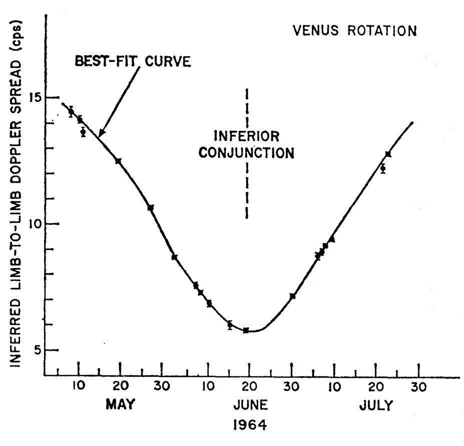

Fig. 2. Inferred limb-to-limb Doppler spread vs date for observations of Venus taken at the Arecibo Ionospheric Observatory during 1964. The solid curve represents the least-mean-square fit to the data and corresponds to a rotation period of 245.1±2 days and a rotation axis inclined by −89.8±1 deg to the ecliptic.

V. MERCURY OBSERVATIONS

Data useful for determining the rotation rate of Mercury were obtained in April and August 1965. Despite the less favorable circumstances of the inferior conjunction in August, improved operating procedures and equipment permitted measurements to be made whose quality equaled or surpassed those of April. All data in April were obtained using transmitted pulses of 0.5 msec in length. Although, with such a pulse, useful results were obtained for delays up to 1.5 msec on one occasion, the useful data in all other cases were limited to delays of 1.0 msec relative to that for the subradar point.

During August, both 0.5 and 0.1 msec pulses were used; with the latter it was possible to observe at delays up to 0.4 msec. Although the frequency spreads in this case are smaller, they are nevertheless well resolved and their greater number offered an excellent opportunity to verify internal consistency as may be judged from Fig. 3. Data obtained using both pulse widths agreed well, as shown in Fig. 4, where the extrapolated values for limb-to-limb Doppler bandwidth are plotted vs date of measurement for all the 1965 observations at AIO. Table III contains the data plotted in Fig. 4. In the calculations the radius of Mercury was assumed to be 2420 km (Allen 1964). The measurement errors indicated were obtained from a consideration of the internal consistency of the results for a given day and the estimated accuracy in determining the positions of the wings of the spectra.

Mercury's rotation vector could be estimated from the inferred limb-to-limb Doppler bandwidths as mentioned in Sec. II. Because of the smaller arc of the orbit over which observations were made, however, the determination of the axis direction would not be nearly so accurate for Mercury as for Venus. Therefore, at first the axis was constrained to lie perpendicular to the plane of Mercury's orbit. The sum of the squares of the differences between the measured and calculated

TABLE III. Bandwidth data from 1965 radar measurements of mercury.

Date (1965)	Time (UT) h m	Pulse length (msec)	Inferred limb-to-limb Doppler bandwidth (cps at 430 Mc/sec)
6 April	17 00	0.5	19.0±1.0
10 April	16 15	0.5	19.4±2.0
12 April	16 15	0.5	20.1±1.0
25 April	15 30	0.5	16.0±1.5
2 August	18 00	0.5	17.3±2.0
10 August	17 00	0.1	17.8±1.5
17 August	16 00	0.1	18.7±1.0
20 August	16 00	0.1	18.7±1.0
24 August	16 00	0.1	18.1±1.2

values was then determined for a number of possible values for the rotation period. This sum was found to be a minimum for an assumed period of 59 days and to double for periods of 56 and 62 days. With the constraint on the axis direction removed, a period of 56 days and an axis direction 28° from the normal to the orbital plane were obtained; the sum of the squares of the residuals was nearly the same as for the constrained 59-day case. Thus, we have concluded from these data that the axial rotation period of Mercury is 59±3 days and that its axis is pointed within 28° of the normal to its orbital plane.

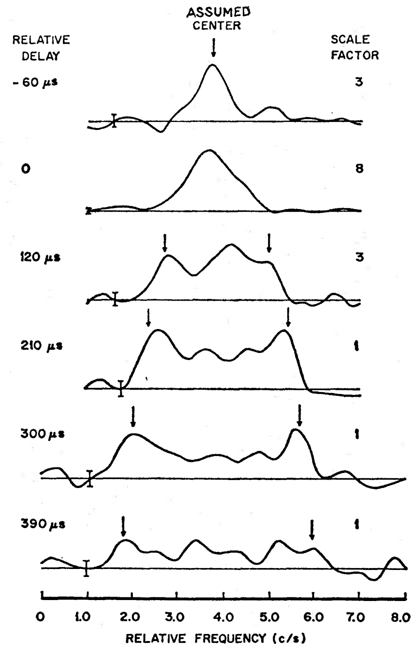

FIG. 3. A plot of the spectrum of radar echoes from Mercury on 17 August 1965 as a function of delay (relative to the observed position of maximum intensity). Scale factors shown represent the value by which that spectrum has been divided in order to present the results. The pulse width used was 100 μsec; thus the bottom five spectra are essentially independent of each other. The spectral resolution is 0.5 cps. Arrows indicate the expected positions of the wings of the spectra under the assumption of a 59 day (direct) sidereal rotation period with axis normal to Mercury's orbital plane.

V. VENUS SURFACE MARKINGS

In the course of the delay–Doppler processing of the Arecibo data, a variety of nonuniformities in echo strength have been evident. These can be considered as "features"—and are presumably related to anomalous surface conditions. The preliminary analysis by JPL of its data from the inferior conjunction of Venus in June 1964 (Goldstein 1965) disclosed two such features which were named "Alpha" and "Beta." Examined in Doppler coordinates without delay resolution, these features appeared to drift across the planet as it rotated. Their longitude and approximate latitude were deduced from the change with time of the relative Doppler frequency of each feature. The Arecibo data have been examined to confirm the presence of anomalously high reflectivities in the Alpha and Beta regions. Region Alpha appeared clearly in the data obtained on 23 July 1964, which, by coincidence, was the day that it passed across the central meridian (see Fig. 5). Although not wider than 900 km in longitude, Alpha exhibits significant internal variations in radar reflectivity. Its longer dimension is probably in excess of 3800 km and lies approximately parallel to the coordinate lines of constant Doppler shift. On an earlier day, 9 July, the feature was located on the approaching side of the planet, while appearing to maintain its linear shape, as shown in Fig. 6. The line might actually have been longer on this date but is

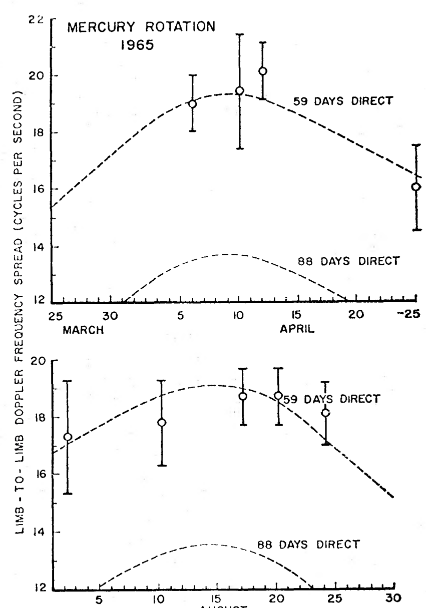

FIG. 4. Inferred limb-to-limb Doppler spread vs date for observations of Mercury taken at the Arecibo Ionospheric Observatory during 1965. The dotted curves show the theoretical variation for direct sidereal periods of rotation of 59 and 88 days, under the assumption that the axis of rotation is normal to the orbital plane of Mercury.

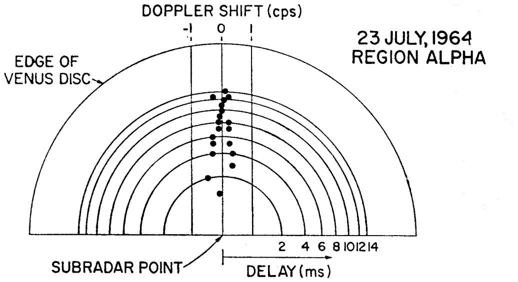

FIG. 5. Schematic diagram of Venus in delay–Doppler coordinates, showing the locations of peaks in the values of radar reflectivity for 23 July 1964. The central meridian for this date corresponds roughly with the region Alpha (see text). Only half the disk is presented because of the unresolved hemispheric ambiguity. Observations at JPL (Goldstein 1965) indicate that region Alpha is confined to the southern half of the disk.

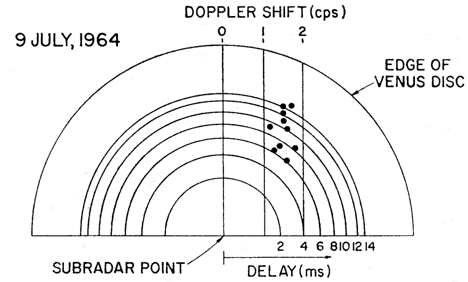

FIG. 6. Schematic diagram of Venus in delay–Doppler coordinates for 9 July 1964. Compare with Fig. 5.

limited at one end by the unfortunate termination of the sampling at 14.5 msec delay and at the other by confusion with the "wing" corresponding to the 4 msec delay annulus. (Incidentally, the movement of Alpha between 9 July and 23 July corresponds to a rotation with a retrograde sidereal period of 240 ± 50 days.)

Region Beta is more extensive (as shown earlier at JPL) and consequently, with a 1 msec delay resolution, appears as a complex region in the Arecibo data. To make this more evident, a contour map of echo strength observed on 19 June is presented in Fig. 7 in delay–Doppler coordinates. So far, no attempt has been made to resolve the northern–southern hemisphere ambiguity. The JPL study, however, suggests that the region Beta lies above 10 deg in the northern hemisphere. A cursory examination of the data obtained on other dates indicates that the detailed pattern of the radar reflectivity changes with the changing orientation of the planet, but that the region Beta remains a strong backscatterer of radar waves.

VI. DISCUSSION AND CONCLUSIONS

The determination of the rotation period of Venus from the 1964 radar measurements is sufficiently accurate to encourage the IAU to agree on establishing surface coordinates on Venus so that, for example, radar measurements of surface characteristics made by different observatories can be compared easily. From the work reported here and from the similar results obtained by the Jet Propulsion Laboratory (Goldstein 1965; Carpenter 1966), it appears as though a basis could be found for a suitable definition of a coordinate system for the surface of Venus.

The rotation period found for Venus suggests that its axial motion may be controlled by the earth since retrograde rotation with a period of 243.16 days implies that Venus presents the same "face" to the earth at every inferior conjunction. It is hard to understand both how such a rotational state was reached and how it could be dynamically stable. Several groups (e.g., Goldreich and Peale 1966; Shapiro 1966; and Bellomo *et al.* 1966) have studied the dynamics of the rotation but none has found a satisfactory solution.

The value of 59 ± 3 days for the axial rotation period of Mercury, although not nearly so well determined as that of Venus, appears to be quite consistent with almost all of the optical data (McGovern, Gross, and Rasool 1965; Colombo and Shapiro 1965; Dollfus 1966) and with theoretical analyses (e.g., Peale and Gold 1965; Colombo and Shapiro 1965). In fact, Colombo (1965) pointed out the possibility that Mercury's rotation period might be 58.65 days, i.e., exactly two-thirds of its orbital period. This value of the rotation period would apparently make Mercury unique in the solar system in having its axial motion locked to its orbital motion in such a manner. The dynamic stability and the possible evolution of Mercury's axial rotation are actively being investigated by many groups. The key element in the preferred status of the two-to-three relation is the large eccentricity of Mercury's orbit. This eccentricity allows the solar tidal torque to change

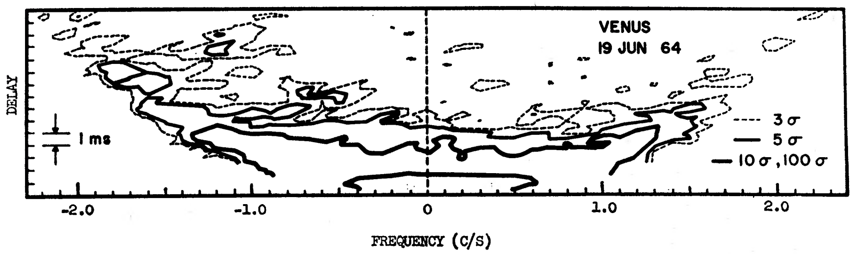

FIG. 7. Contours of echo strength (in units of the standard deviation, σ, of the system noise level) as a function of delay and Doppler for Venus as observed at the AIO on 19 June 1964 (inferior conjunction). Region Beta (see text) appears as a scattered group of strong echoes on the left side of the diagram.

sign during an orbital revolution (Peale and Gold 1965) and leads to an asymptotically stable spin state (Bellomo *et al.* 1966).

Note added in proof: Using a radius of 6055 km for Venus, as found by Ash *et al.* (1967), we obtain a sidereal rotation period of 244.3±2 days with an axis direction specified by $\delta=-66.4\pm1$ deg and $\alpha=90.9\pm1$ deg (1950.0).

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