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Final Technical Report

on the

ANALYSIS OF MARINER 5 RADIO TRACKING DATA

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Principal Investigator: Irwin I. Shapiro

Irwin I. Shapiro
Professor of Geophysics
and Physics
Soc. Sec. No. [redacted]
Tel. (617) 253-5734

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Analysis of Mariner 5 Radio Tracking Data

I. Introduction

Support was originally sought to analyze Mariner 5 radio tracking data to extract information of interest for tests of theories of gravitation. At that time, it was thought that Mariner 5 could be tracked in heliocentric orbit perhaps for several years so that the tracking data, in combination with radar ranging data, might provide a useful determination of the solar gravitational quadrupole moment and of the relativistic contribution to the advance of the orbital perihelion. No significant tracking data were obtained after Venus encounter and so these original goals had to be abandoned. Instead we adopted the following goals: (i) the determination of the mass of Venus (to check, and perhaps improve upon , the value obtained at the Jet Propulsion Laboratory); (ii) the determination of, or the placement of a stringent upper bound on, the second-order terms in the harmonic expansion of Venus' gravity field; and (iii) an independent estimate of the locations of the Deep Space Net (DSN) tracking stations relative to the coordinate system defined by the orbits of the planets. To this list we added a fourth goal, helpful to the achievement of the second but necessary only to the understanding of the result, namely the determination of the rotation vector of Venus. This last task involved the analysis of radar observations of Venus and utilized only a small portion of the grant.

What were the scientific reasons for pursuing these goals? The mass of Venus is a fundamental solar-system constant, important to determine for several reasons of which we list two: (i) for the constraint it places on theories of the origin and evolution of the solar system, both directly and indirectly in relation to the planet density; and (ii) for the proper calculation of the perturbations Venus introduces into the orbits of other planets. In regard to the first reason, only low accuracy is required in consideration of the present state of the relevant theories and so the Mariner 5 data are not crucial. The situation is quite different in regard to the second reason. One of the main means for tests of theories of gravitation is through the determination of the relativistic part of the advance of the perihelion of Mercury. The perturbations due to Venus cause an advance in Mercury's perihelion of over 250 arcseconds per century as compared with the approximately 43 arcseconds per century relativistic contribution. Thus, for precision tests of gravitation theories, very accurate estimates of Venus' mass are required.

Knowledge of the second-order terms in the harmonic expansion of Venus' gravity field are important in the determination of (i) any deviation of Venus' mass distribution from a condition of hydrostatic equilibrium, and (ii) the gravitational torque that the earth exerts on Venus. This second aspect is of great interest because of the apparent control the earth exerts on Venus' spin. Venus' spin seems to be in resonance, or nearly in resonance (see below), with the relative orbital motions of earth and Venus. If this resonance is bona fide, and not simply a coincidental near resonance, it is hard to conceive of any interaction other than gravitational through which the earth could exercise its control. Such control would be through a torque proportional to the fractional difference in Venus' principal equatorial moments of inertia or, equivalently, to the magnitude of the second tesseral harmonic. In the determination of these second-order gravity terms from an analysis of the tracking data, it is helpful to have a reasonably accurate independent value for the direction of Venus' pole. Such information can come only from the radar observations. Similarly an answer to the question of the existence of the spin-orbit resonance for Venus can come, at present, only from an analysis of the radar data. For these coupled reasons we added such an analysis to the goals under this grant.

A determination of the locations and the uncertainty in the locations of the tracking stations of the DSN, relative to a planetary coordinate system, is important not only for spacecraft navigation but to assess the usefulness of spacecraft tracking for the establishment of an accurate worldwide geodetic grid. Although sparse, because of the paucity of stations, the DSN positions have been used as a standard, or benchmark, by other organizations employing other techniques to set up a global grid. Until our analysis was undertaken, there was no determination available other than JPL's.

In the succeeding sections of this report, we discuss, in turn, the analysis of the radio tracking data to meet the three goals outlined, and the analysis of the radar observations of Venus to determine its spin vector.

II. Tracking Data Analysis

The Mariner 5 tracking data used in our analysis consisted of (i) about 2650 two-way average Doppler shift observations, with the averaging interval being 10 min for all the data except for those near Venus encounter; and (ii) 214 two-way time delay, or ranging, observations. The Doppler data span the period from 19 September 1967 to 24 October 1967; encounter was on 19 October 1967. The ranging data were all obtained in an 8-day period near encounter at Deep Station Station (DSS) 14. The Doppler data were obtained at DSS's 11, 12, 14, 41, 42, 61, and 62. The first three are located at Goldstone, California; the following two in Australia; and the last two in Spain.

The analyses were carried out using the MIT Planetary Ephemeris Program (PEP), a versatile computer program capable of estimating a wide variety of parameters from a large number of different types of observations.

1. Mass of Venus

A multitude of solutions for Venus' mass was made to test the result for sensitivity to possible errors in the models used for the propagation medium, the non-gravitational forces (sunlight pressure and gas leaks), and the planetary ephemerides. In addition, the sensitivities to the inclusion or exclusion of parameters for the higher-order terms in the gravity field expansion, to the length of the data arc, and to the relative weightings of the range and Doppler data were investigated. The results of this fairly comprehensive search for the effects of all likely sources of systematic error in the mass estimate lead us to conclude that

$$M_{♀}^{-1} = 408{,}523.5 \pm 1.0\,, \tag{1}$$

where the result is expressed in units of the inverse solar mass. The error quoted represents our best judgment of the equivalent standard error in the estimate of the mass in the face of the various systematic errors. The formal standard error for most of these solutions, based on setting the rms of the weighted postfit residuals to unity, was 0.04 -- a factor of 25 lower. This comparison illustrates that the results are dominated by systematic errors. As an illustration of the effects of such errors on the postfit residuals, we exhibit them for a typical solution in Figure 1. The rms of the residuals is only about 5 mHz, but the systematic trends are blatant, thus demonstrating, as well, the low level of the random noise affecting the data. The increase in the scatter of the residuals near encounter is simply a manifestation of the shorter averaging time and the consequent increase in the effect of the random noise. The density of points in this region is so great as to obscure the systematic trends which are present here as well.

We may compare our result for the mass of Venus with that last published by JPL [cf. J. D. Anderson and L. Efron, Bull. Amer. Astron. Soc. **1**, 231 (1969)] which was $M_{♀}^{-1} = 408{,}522 \pm 1$; our value for the mass is thus slightly lower, but not significantly so. A recent reanalysis by JPL (N. Mottinger, private communication) of the Mariner 5 data, however, also yields a slightly lower value, very close to our result, as does our preliminary result of 408,523.9±1.2 for the inverse mass [H. T. Howard et al., Science 183, 1297 (1974)] from the analysis of the Mariner 10 data.

2. Harmonic Coefficients for Venus' Gravity Field

There is a very serious impediment to the reliable estimation of any of the coefficients of the spherical harmonic expansion of Venus' gravitational potential. From a single flyby it is not possible to obtain useful estimates of a large number of these coefficients. Since we have little *a priori* basis for the neglect of all harmonic coefficients of degree higher, say, than the second, but since we must make *some* such assumption in order to obtain any credible result, our estimates for the second-degree coefficients will inevitably be somewhat suspect.

With that *caveat* in mind, we solved for the second-degree coefficients and tested the sensitivity of the resultant estimates to the inclusion of third- and fourth-degree terms in the parameter set. The addition of these latter parameters led to estimates for the second-degree terms which made little physical sense and confirmed our *a priori* judgment about the difficulties attendant to attempts to estimate harmonic coefficients from a single flyby. However, with the coefficients of the gravity field limited to second degree, we did obtain solutions that were fairly stable in the face of the same sensitivity tests as were described above in connection with the estimate of Venus' mass. Thus, our values for J_2, the coefficient of the second zonal harmonic, were almost all in the range

$$J_2 = (1.6 \pm 0.4) \times 10^{-5}. \qquad (2)$$

The value published by JPL (Anderson and Efron, *op. cit.*) was $J_2 = (-0.5 \pm 1) \times 10^{-5}$, which is not in good agreement with our result, differing from it by about twice the error they quote. Of course a planet with a negative J_2 is rotationally unstable and thus it is unlikely that this solution is correct. A more recent JPL analysis by N. Mottinger (private communication) gave values of J_2 from 2.08×10^{-5} to 4.34×10^{-5} with errors from 0.26×10^{-5} to 0.85×10^{-5}.

The coefficients of the second-degree tesseral terms were less stable, but remained consistently below about 2×10^{-6} in magnitude. If we were to take this bound seriously, we would conclude that the fractional difference, $(B-A)/C$, in the principal equatorial moments would be bounded by

$$\frac{B-A}{C} < 2.5 \times 10^{-5}, \qquad (3)$$

since

$$J_{22} = \frac{B - A}{4M_{♀}R_{♀}^2} \simeq \frac{B-A}{12C} \;, \qquad (4)$$

where $R_{♀}$ is Venus' equatorial radius and J_{22} is the magnitude of the coefficients of the second-degree terms. Such a bound as given in Equation (3) would make it very difficult to understand how the earth could control Venus' spin [see, for examples, P. Goldreich and S. J. Peale, Astron. J. 72, 662 (1967); E. Bellomo, G. Colombo, and I. I. Shapiro in Mantles of the Earth and Terrestrial Planets, ed. S. Runcorn (Interscience, London, 1967), p. 193]. In view of the systematic errors clearly present in the residuals (see Figure 1), as well as the arguments adduced above, we consider it inadvisable to draw any firm conclusions in regard to a bound on (B-A)/C for Venus.

Better prospects lie in the combination of the Mariner 5 and the Mariner 10 data, as was mentioned in our earlier report (letter of Dr. N. Roman, 11 November 1971). Since Mariner 10 did not fly by Venus until after the expiration of this grant, no such analysis could have been undertaken with this grant. However, we are pursuing this investigation, as yet incomplete, through our membership in the Mariner 10 Radio Science Team. Definite conclusions may still have to await the receipt of tracking data from the Pioneer Venus Orbiter Mission.

3. DSN Station Locations

The Doppler, and limited range, data available are sensitive primarily to only two of the three coordinates that serve to locate a Deep Space Station -- the longitude, λ, and the distance, r_s, from the earth's spin axis. The Doppler data are intrinsically insensitive to the third cylindrical component, the distance from the equatorial plane; the range data are apparently neither extensive nor accurate enough to improve on the ground survey estimates of the third component. The data were analyzed and studied to determine the values for λ and r_s for each of the participating Deep Space Stations. The same techniques were used as described in Section II. 1.

The most curious aspect of the results was an apparent inconsistency between the Doppler and range data. When the range data are downweighted, the postfit range residuals show a large bias and a significant slope as well as other systematic effects within a single pass. These residuals are shown in Figure 2. The bias amounts to about 15 μsec and seems too large by about a factor of 3 or more to be explained as an ephemeris error, although that possibility can not be ruled out completely. Further, when the range data were included with appropriate weighting (assumed standard error of 0.3 μsec for each point), the solutions for the station longitudes changed dramatically -- by about 10 m -- despite the change in the spacecraft's position in inertial space accounting for only slightly over a 1 m displacement in station longitude*. The systematic trends in Doppler residuals also increased noticeably when the range data were properly weighted. No satisfactory explanation has been found for this apparent inconsistency between the range and Doppler data. Contacts with the JPL personnel that were involved with the relevant equipment yielded no clues. In the JPL determinations of station locations from the Mariner 5 data, the ranging data were simply ignored. This solution to the apparent inconsistency seems unsatisfactory to us in the absence of any specific reason to suspect the ranging data of being corrupted by large systematic errors.

To be specific, we show in Table 1 a comparison for λ and r_s for each station for solutions with the range data weighted and with the range data unweighted. (The solution for DSS42 has been omitted since few Doppler

*Note that the estimates for Venus' mass and harmonic coefficients are insensitive to the relative weighting of the range and Doppler data.

points were available from this station.) The differences in the longitudes are between 10 and 12 m; the differences in the r_s's are all under 3 m. Thus we have, in effect, "tunable" coordinates: We can vary the solutions primarily for the longitudes over at least this 12 m interval by simply varying the relative weightings of the range and Doppler data.

Although the "absolute" longitudes (relative to the coordinate system defined by the planetary ephemerides) is strongly affected by this range-Doppler problem, the relative longitudes are more stable. We therefore compare in Table 2, for a typical spacecraft-data solution, the differences in the coordinates for DSS12 and DSS11, DSS12 and DSS14, and DSS61 and DSS62 with the ground survey values*. The relative values from the spacecraft-data analysis and the ground survey differ in no case by more than twice the formal standard error associated with the spacecraft solutions. However, we note that for this

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*Only the relative locations were determined accurately in the ground surveys.

comparison the near-encounter Doppler data obtained at DSS14 were omitted.

Most of the work reported here was carried out by Stephen P. Synnott as part of his doctoral research. A complete discussion of the tracking-station location analysis can be found in his August 1974 MIT doctoral dissertation which contains, as well, an analysis of the Mariner 4 and Mariner 9 tracking data. Dr. Robert D. Reasenberg of the MIT staff carried out part of the analysis leading to the estimates of the mass of Venus and the coefficients of the second-degree terms in the harmonic expansion of its gravity field. The analysis of the Mariner 5 data was originally started by Louis D. Friedman, then an MIT graduate student.

Two papers are planned for publication based at least in part on this work -- the first on the combined analysis of the Mariner 5 and Mariner 10 tracking data as they relate to the determination of Venus' mass and gravity field, and the second on the determination of the location of tracking stations from Doppler and range data.

III. Radar Data Analysis

Since Venus' thick cloud cover prevents optical observation of its surface, only radar data are available for a precise determination of its spin vector. Prior results [I. I. Shapiro, Science 157, 423 (1967); R. L. Carpenter, Astron. J. 75, 61 (1970); and R. F. Jurgens, Radio Science 5, 435 (1970)] indicated that the spin period of Venus was perhaps 0.1 to 0.2 days lower than the resonance value of 243.16 days (retrograde). However, each of these analyses was based on a relatively small sample of the relevant data and was not of sufficient accuracy to conclude reliably that the differences from the resonance value were significant.

We have therefore attempted to obtain as much of the data as were available and to analyze all of it simultaneously to improve upon prior determinations of the spin vector, primarily to ascertain whether we could distinguish reliably between resonant and non-resonant rotation. These data are of three general types: (i) bandwidths; (ii) spectra; and (iii) delay-Doppler maps. The bandwidth data consist of measurements of the total bandwidths of echoes confined to returns from particular delay "rings" on the planet. The spectral data consist of echo power displayed as a function of Doppler shift; these are of two kinds: polarized and depolarized, with the former representing the echo in the "expected" sense of polarization (for a spherical reflector) and the latter in the opposite sense. The delay-Doppler maps present the echo power as a function of both delay and Doppler shift. The bandwidth data depend directly on all three components of the spin vector and can be inverted uniquely to obtain estimates of these components. The spectral data are useful only insofar as one can successfully identify "features" in the spectra and, most importantly, correctly associate the features on spectra obtained at different times: It is the spectral history of a particular surface feature that contains the information both on its latitude and longitude and on the spin vector of Venus. The association of features present on different spectra is in general very difficult to make properly because of the effect of "blending". Each part of a spectrum contains echoes from an entire strip on the planet [see, for example, I. I. Shapiro *et al.*, *Science* **178**, 939 (1972) for a simple discussion of this and the other relevant properties of radar echoes from planets], and it is not possible *a priori* to say which part or parts of the surface are contributing to a given spectral feature. Because of the changes in the apparent rotation vector, which is composed of contributions from the sidereal spin vector and the relative orbital motions of the earth and Venus, the spectra obtained at different times contain at any given part contributions from different parts of the surface. Two parts of the surface which contribute to the same part of the spectrum at one epoch will, in general, contribute to different parts of the spectrum at another epoch. To make matters even more difficult, the backscattered power from a given surface feature may well vary with the aspect from which it is viewed*. In summary, these various awkward characteristics of the spectral data inject a certain amount of subjectivity into the analysis, the possible consequences of which must always be borne in mind.

The delay-Doppler maps also suffer from ambiguity. Without the use of interferometry or a narrow enough antenna beam, there is in general a two-to-one "hemispheric" ambiguity in the association of a physical portion of the surface with a particular set of delay-Doppler coordinates. However, this ambiguity is far less trouble-

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*This problem can be alleviated by making use of the fact that every eight years Venus and the earth are both in almost exactly the same orbital configuration.

some in practice since the probability of blending is vastly reduced compared to the case for spectra. One might wonder why spectral data should be used at all if the delay-Doppler maps and the bandwidth data are apparently so superior. The answers are simple. The bandwidth data do not afford the possibility to "track" a surface feature and so the accuracy in the determination of the spin period will not increase in direct proportion to the time span of the observations as for feature observations. The delay-Doppler maps, on the other hand, do not cover as long a time span as the spectral data and, moreover, are of lower signal-to-noise ratio because of the two-dimensional dilution. In fact, some of the earlier maps are of marginal use because of the poor signal-to-noise ratios then available.

The data used in our analysis were obtained from the Arecibo Observatory, the Goldstone Tracking Station, and the Haystack Observatory. From Arecibo, delay-Doppler maps were obtained for the periods near the inferior conjunctions of Venus in 1964, 1967, 1969, and 1972; bandwidth data were also obtained for the first three of these conjunctions. From Goldstone, we obtained only spectral data, both polarized and depolarized, for the 1962, 1964, and 1966 inferior conjunctions. From Haystack, spectral data, both polarized and depolarized, were available for the 1966, 1967, 1969, 1970, and 1972 inferior conjunctions with delay-Doppler maps from 1969 and 1972.

Feature associations were determined by a trial and error iterative process utilizing, in part, machine computation of expected feature position in either the Doppler coordinate for spectral data, or the delay and Doppler coordinates for map data. The final analysis, given the presumably proper feature associations, were performed both with PEP and with a special-purpose program written specifically to determine planetary spin vector components from the various types of radar data.

In Figure 3, as an illustration, we show two depolarized spectra, taken eight years apart, the earlier one at a radar frequency of 2388 MHz (S-band) at Goldstone in 1964 and the later one at a radar frequency of 7850 MHz (X-band) at Haystack in 1972. The features were all labelled with names of 19th century physicists who contributed importantly to the development of electromagnetism. In Figure 4 we show a part of a delay-Doppler map obtained at Haystack which contains contours of equal reflective power relative to the mean backscattering law for the whole region; the same features are identified as on Figure 3, plus several additional ones.

1. <u>Spin Vector of Venus</u>

If Venus' spin were in resonance with the relative orbital motions of the earth and Venus, we would expect that its spin period would be -243.16 days (retrograde) and that its spin axis would have coordinates (1950.0): $\alpha = 278^\circ\!.54$, $\delta = 67^\circ\!.2$, corresponding to the direction of the negative of the spin angular momentum vector. What in fact did our analyses yield? Naturally, they are not yet definitive! Considering all the data simultaneously yielded:

$$P = -243.03 \pm 0.01$$
$$\alpha = 273.0 \pm 0.2$$
$$\delta = 67.6 \pm 0.2$$

On the other hand, for example, with only the Arecibo delay-Doppler data utilized, we obtained in a typical solution*:

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*As in Section II, we tested the sensitivity of our solutions to many variations in both the parameter and the data sets as well as in the data weights.

$$P = -243.10 \pm 0.03$$

$$\alpha = 273.0 \pm 0.4$$

$$\delta = 67.0 \pm 0.4$$

where, in each case, the formal standard error is given, based, by definition, on setting the rms of the weighted postfit residuals to unity. The disparity between the results, coupled with some systematic trends in the residuals, leads us to the obvious conclusion: the errors in the estimates for the spin vector are being dominated by systematic effects. We are currently re-examining all of the data to select only those that are most reliable and to make better use of the eight-year-cycle relationships.

Upon completion of this analysis, we intend to submit for publication a rather extensive discussion of these data. In fact, save for the conclusions on the spin vector resonance, the first draft of the paper is already finished. This work was carried out mostly by William De Campli, under my supervision. Clark Chapman was also involved in the early stages. The former was an undergraduate, the latter a graduate student, at MIT at the time this work was started. Mr. De Campli is aiding in the completion of the analysis although he is now a graduate student at Harvard.

Table 1

Comparison of Station Locations

Station and Parameters*	Solution With Doppler Data (km or deg)	Standard Error (m or 10^{-5}deg)	Solution With Doppler and Range Data (km or deg)	Standard Error (m or 10^{-5}deg)	Column 4 - Column 2 (m or 10^{-5} deg)
DSS11 r_s (km)	5206.3389	0.7	5206.3395	0.7	0.6
λ (deg)	-243.150 396	0.9	-243.150 289	0.7	10.7
DSS12 r_s	5212.0514	0.5	5212.0510	0.5	- 0.4
λ	-243.194 339	0.8	-243.194 229	0.4	11.0
DSS14 r_s	5203.9947	0.5	5203.9937	0.5	- 1.0
λ	-243.110 288	0.9	-243.110 163	0.5	12.5
DSS41 r_s	5450.2019	0.5	5450.1997	0.5	- 2.2
λ	-136.887 294	0.7	-136.887 186	0.5	10.8
DSS61 r_s	4862.6065	0.6	4862.6082	0.7	2.7
λ	-355.750 803	0.9	-355.750 694	0.7	10.9
DSS62 r_s	4860.8163	0.6	4860.8189	0.5	2.6
λ	-355.631 982	0.8	-355.631 869	0.5	11.3

*See text for definitions.

Table 2

Comparison of Relative Station Locations with Ground Survey

Stations	Differences in Distances from Spin Axis (km)	Tracking Data Solution Minus Survey (km)	Standard Error from Solution (km)	Differences in West Longitudes (deg)	Tracking Data Solution Minus Survey (deg)	Standard Error from Solution (deg x 10^5)*
DSS12-DSS11	5.7125	0.0008	0.0005	-0.043 942	-1.1	0.7
DSS12-DSS14	8.0567	0.0020	0.0005	-0.034 046	-0.5	0.7
DSS61-DSS62	1.7904	0.0002	0.0005	-0.118 821	-1.4	0.7

*Note that 10^{-5} deg ≈ 1 m on the earth's surface.

Figure Captions

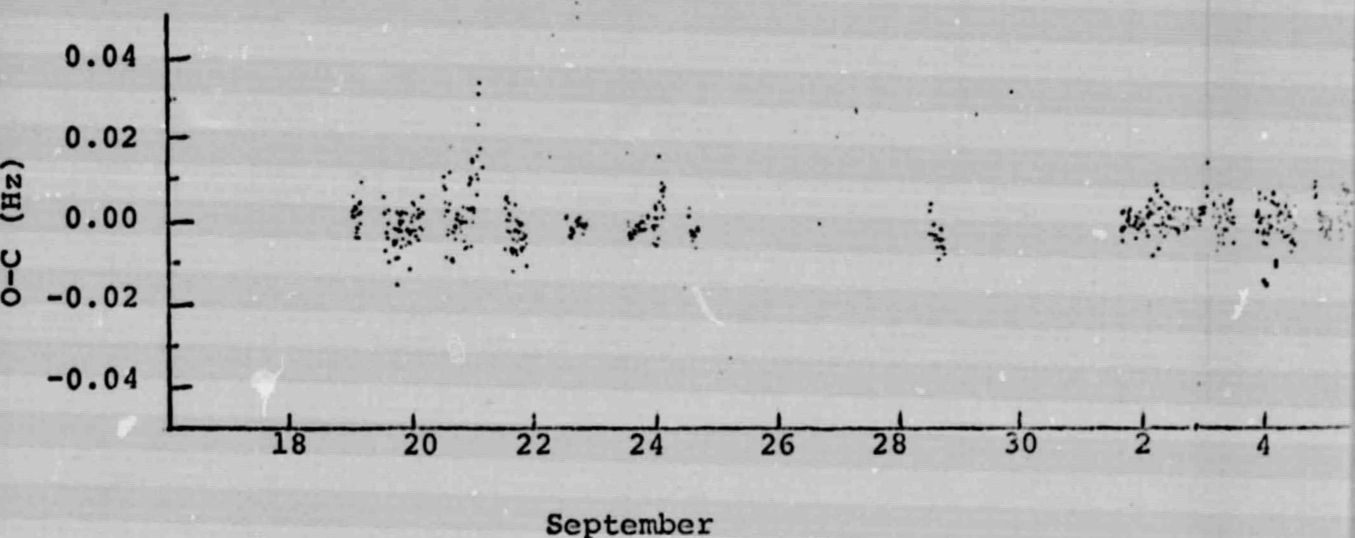
Figure 1. Typical postfit Doppler residuals from an analysis of Mariner 5 radio tracking data.

Figure 2. Typical postfit residuals for the range from an analysis of the Mariner 5 Doppler data.

Figure 3. Comparison of two depolarized spectra of Venus obtained 8 years apart (see text).

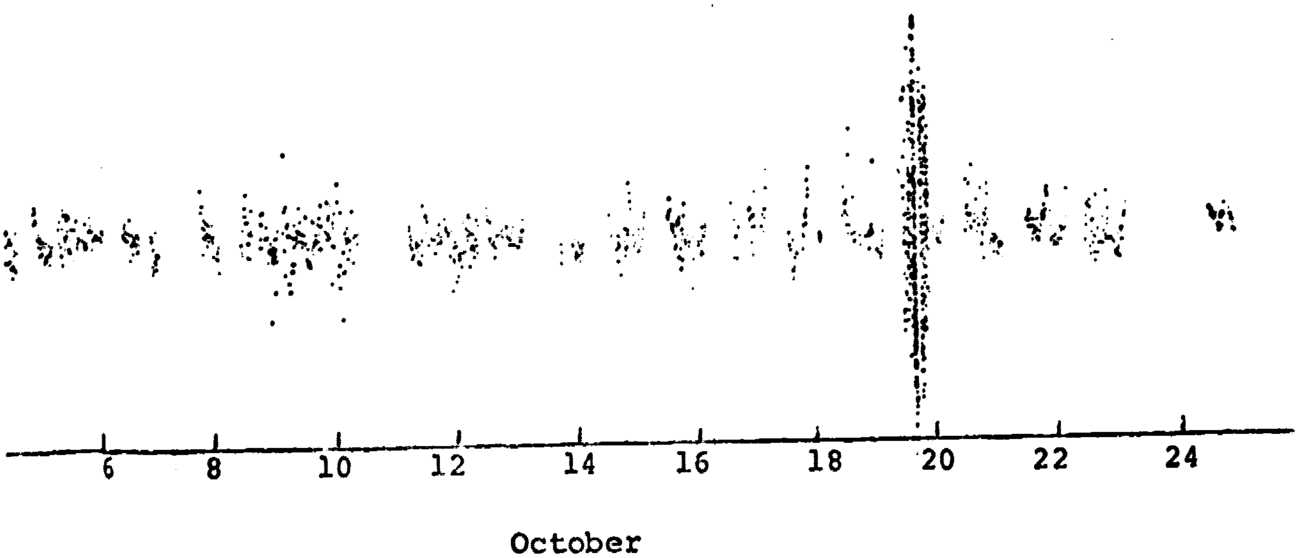
Figure 4. Delay-Doppler Map of a portion of Venus obtained at Haystack in 1972 (see text).

Figure 1



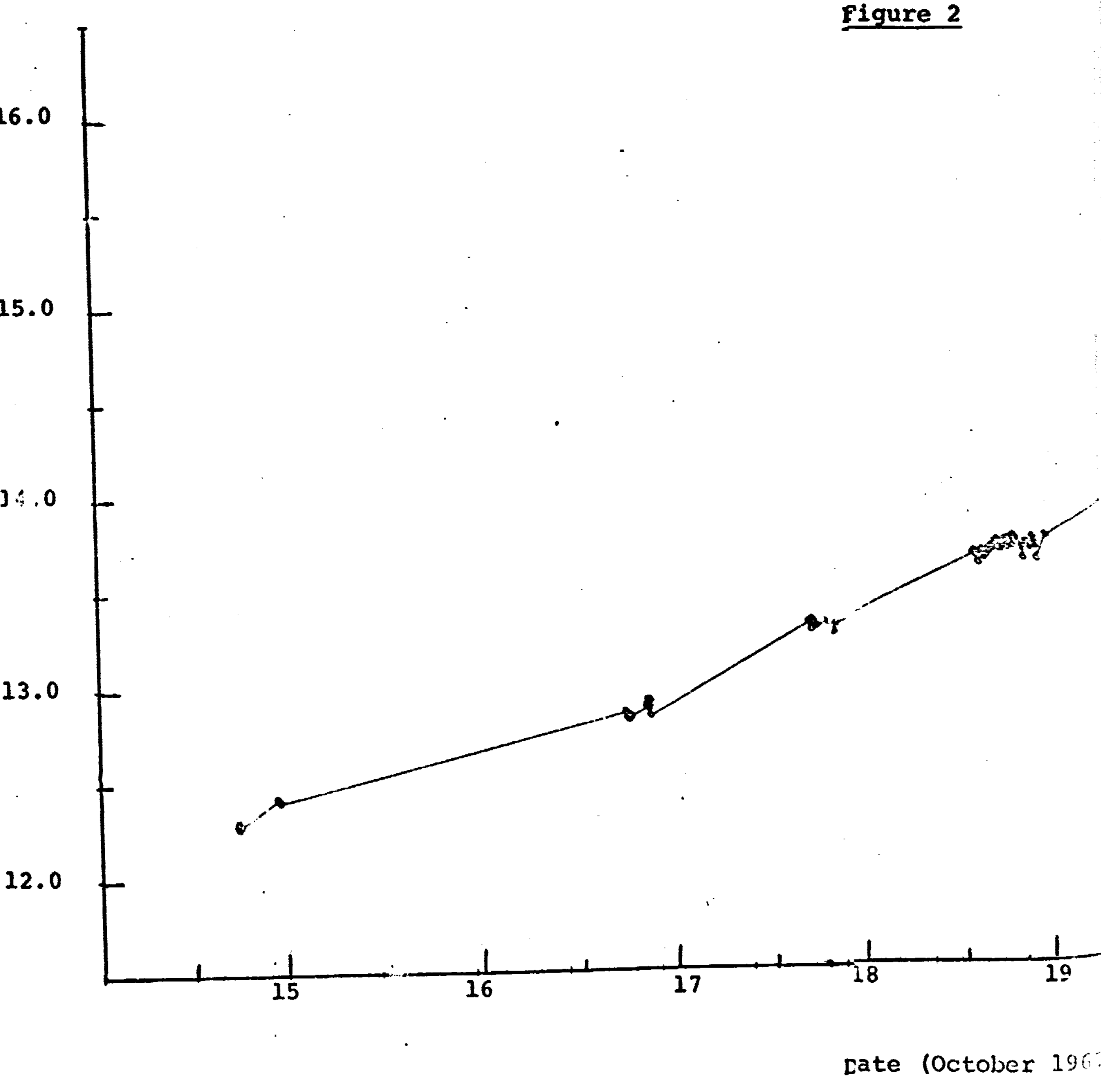
Date (19

e 1

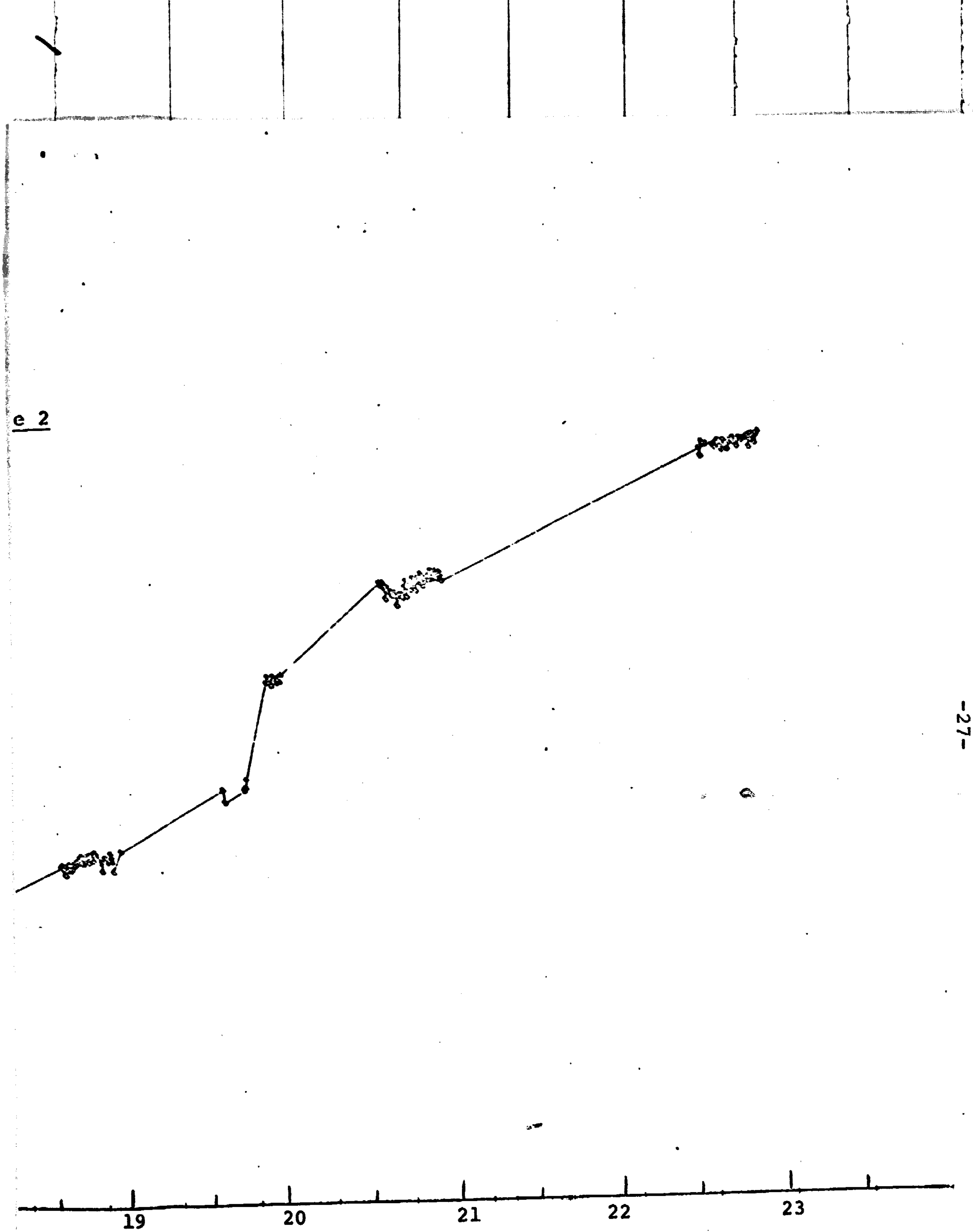


(1967)

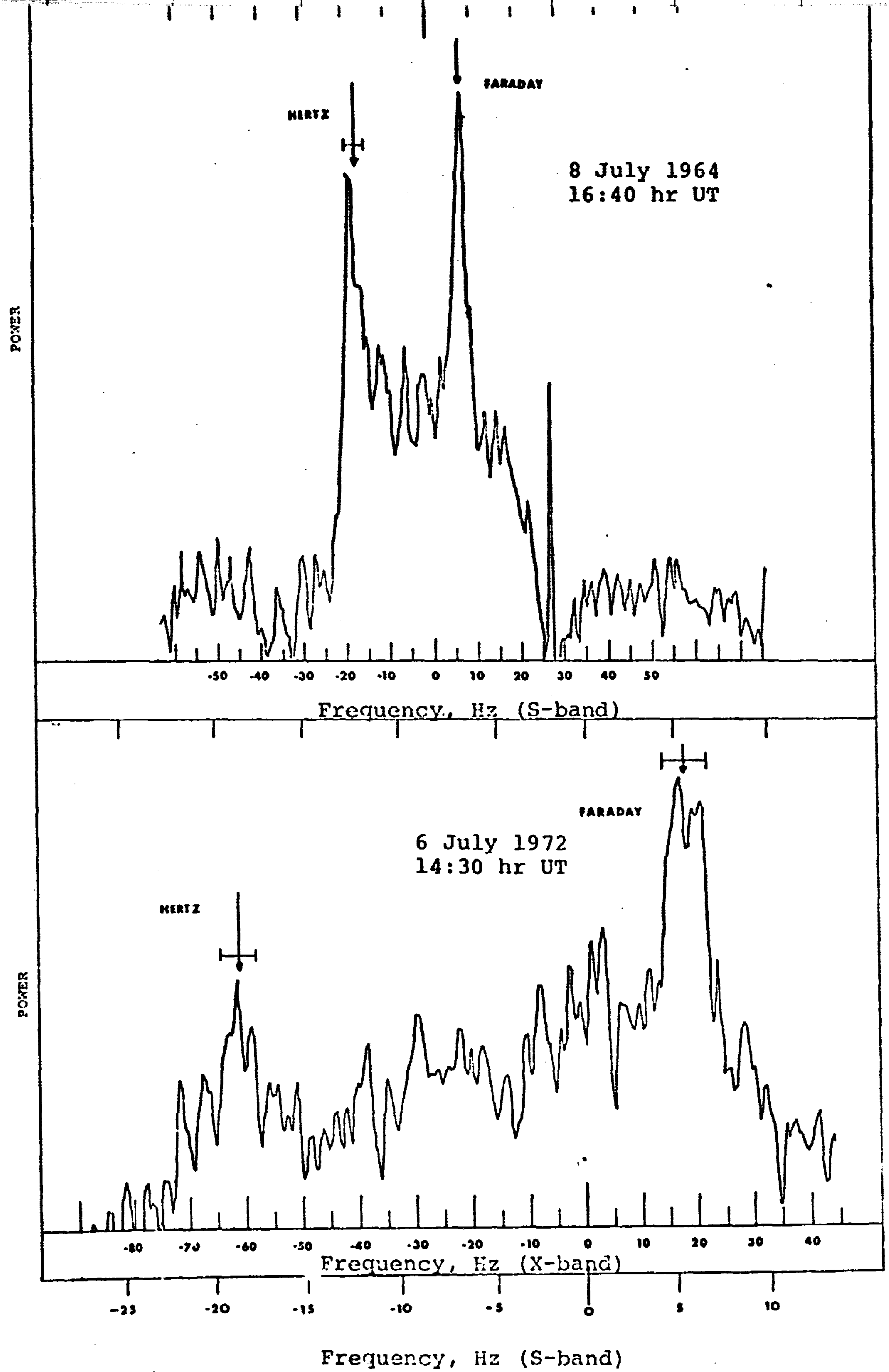
Figure 2

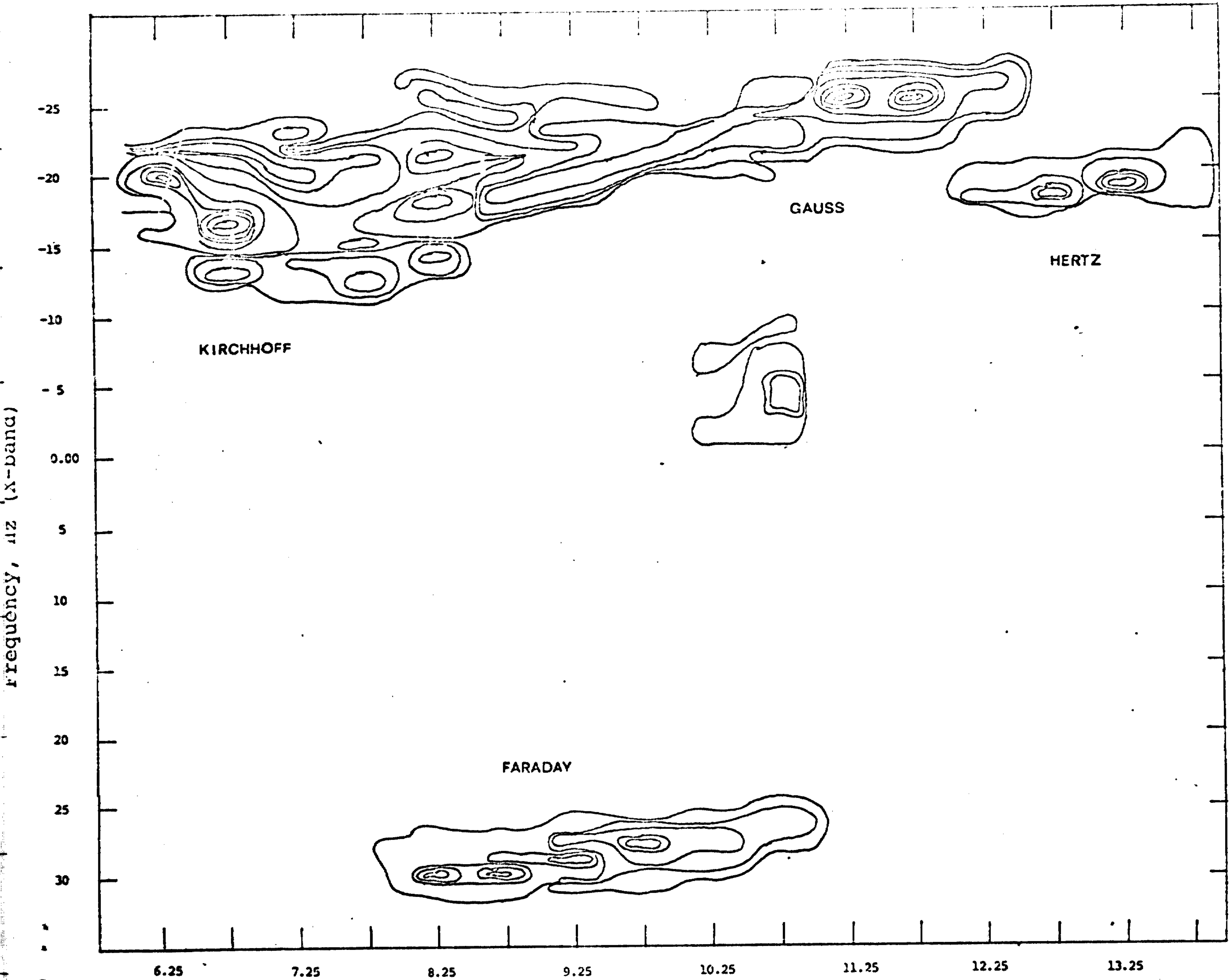


e 2



(October 1967)


FARADAY
HERTZ
8 July 1964
16:40 hr UT
POWER
-50 -40 -30 -20 -10 0 10 20 30 40 50
Frequency, Hz (S-band)
FARADAY
6 July 1972
14:30 hr UT
HERTZ
POWER
-80 -70 -60 -50 -40 -30 -20 -10 0 10 20 30 40
Frequency, Hz (X-band)
-25 -20 -15 -10 -5 0 5 10
Frequency, Hz (S-band)



Frequency, Hz (X-band)
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-20
-15
-10
- 5
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5
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15
20
25
30
KIRCHHOFF
GAUSS
HERTZ
FARADAY
6.25
7.25
8.25
9.25
10.25
11.25
12.25
13.25