The Radius of Venus as Determined by Planetary Radar and Mariner 5 Radio Tracking Data[1]

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During 1967 time-delay measurements from Venus radar bounce signals were obtained as part of a planetary observational program that began in 1961. The mean radius of Venus along with the orbital parameters and other dynamic constants of the planets as well as the astronomical unit have been obtained from a weighted least-squares orbit determination procedure (Ash *et al.*, 1967; Melbourne and O'Handley, 1968). This method provides an estimate of the radius that has various degrees of correlation with the other parameters in the least-squares solution; however, the strength of the radius solution has steadily improved as the number and the precision of the observations have increased and as they have become better distributed. The current estimate of the mean radius of Venus by this method is 6053.7±2.2 km as determined by the Jet Propulsion Laboratory (JPL) (Melbourne *et al.*, 1968). The value obtained by independent observations from the Massachusetts Institute of Technology is 6048±1 km (Ash *et al.*, 1968). The uncertainties are formal standard derivations which assume that measurement errors are independent and have a Gaussian distribution with mean zero.

The radar bounce measurements are contemporaneous with the extremely precise range and Doppler radio tracking measurements of the Mariner 5 spacecraft as it flew by Venus on 19 October 1967. Fig. 1 shows several key aspects of this situation such as the trace of the radar echo zone during the encounter period, the Venera 4 landing site, the Mariner 5 occultation immersion and emersion points, and various radar features on the surface of Venus that have been noted by Goldstein. The near simultaneity of the radar bounce and radio tracking measurements allows one to determine the radius of Venus by a method that is independent of the radar least-squares process and of all radar data except those taken around encounter. Through the perturbation by Venus on the orbit of Mariner 5 during the encounter phase, one is able to determine very accurately from radio tracking data the position and velocity of the center of gravity of Venus as well as its mass. The resulting geocentric range of the center of gravity of Venus at a particular epoch, e.g., the encounter time of Mariner 5, may be compared with an interpolated geocentric range at this epoch based on

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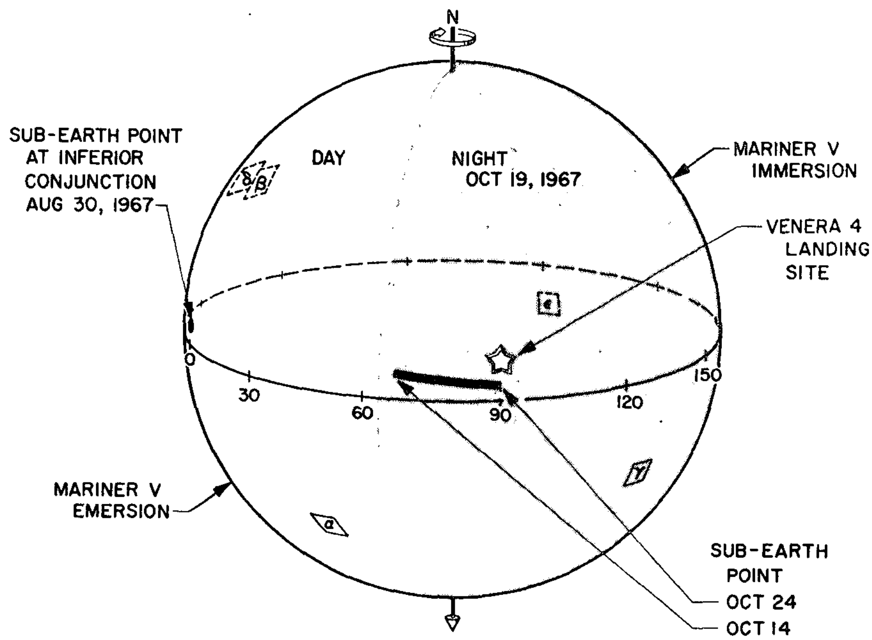

FIG. 1. Venus geometry at Mariner 5 encounter.

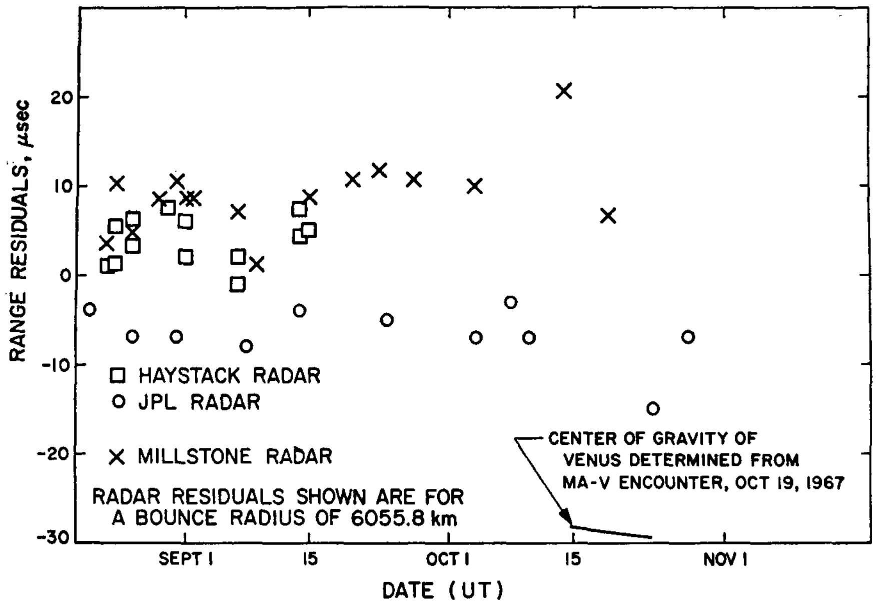

FIG. 2. Two-way range residuals of Venus.

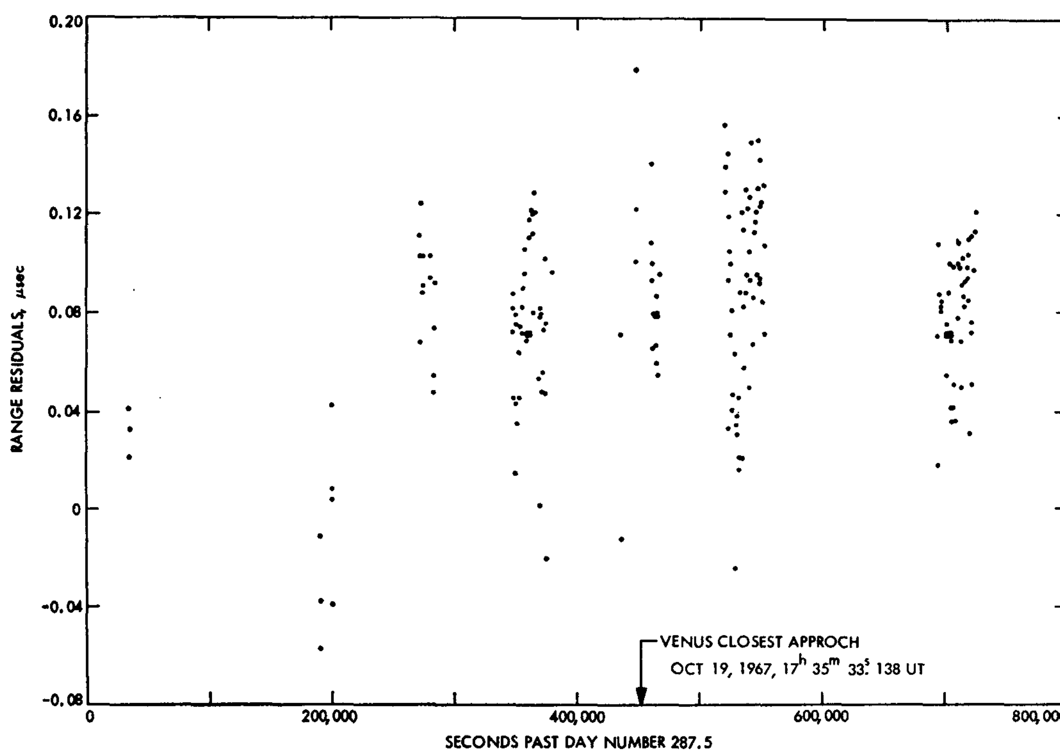

FIG. 3. Two-way range residuals of Mariner V.

the radar time-delay measurements. Since the time-delay measurements of radar bounce signals are referenced from the sub-earth point on the surface of Venus, a value of the bounce radius can be directly inferred from the difference in these two measurement types.

An equivalent method for obtaining this result is to remove the first-order time variable component of the range in both measurement types through a reference ephemeris and then difference the resulting residuals which are slowly varying quantities. Fig. 2 is a plot of two-way range residuals in microseconds vs date. For radar, the residuals are the difference between the observed time-delay and the predicted time-delay based on the reference ephemeris DE 43 (see Melbourne and O'Handley, 1968) and an assumed bounce radius for Venus of 6055.8 km. A reduction in the assumed radius of 1 km reduces the radar residuals by 6.7 μsec. Time-delay data taken near encounter from several radar installations in the United States are shown in Fig. 2. The data from Haystack and Millstone are unpublished and have been received through private communications from the Massachusetts Institute of Technology. The JPL data are in preparation for publication (Goldstein, 1968).

The track shown in Fig. 2 around the Mariner 5 encounter date of 19 October 1967 is the difference in two-way range between the center of gravity of Venus as determined from Mariner 5 radio tracking data and the predicted center of Venus from the reference ephemeris, DE 43. The precision of the Mariner 5 coherent counted Doppler data is 0.5–1.0 mm sec^{-1} sampled once per minute and the precision of the range measurements is about 0.1 μsec (Hamilton,[2] Tausworthe[3]). For these measurement types and the actual distribution of radio tracking data along the Mariner 5 trajectory, it may be shown that the formal standard deviations of the estimates of the geocentric radial position and velocity of the center of gravity of Venus are equivalent to 0.3 μsec in two-way range and 30 μsec per year in two-way range rate. Fig. 3 shows the ranging residuals from Mariner 5 over a 10-day interval around Venus encounter after a converged least-squares solution in which the positions and velocities of Venus and Mariner 5, and the mass of Venus were included.

The JPL radar bounce measurements during this period of time have a precision of about 3 μsec. By adjusting the assumed bounce radius used to generate the radar residuals in Fig. 2 so that the ordinates of the JPL radar points overlap the Mariner 5 track, a Venus bounce radius of 6052.5 km is obtained. This result should be accurate to within 2 km and is in agreement with the mean radius value obtained from the least-squares approach. The radar time delay through the Venus atmosphere has been neglected in obtaining these results. For a Venus atmosphere such as described by Kliore and Cain (1968) with a surface pressure and temperature of 100 atm and 800K, the correction to be added to the radar radius values is about 0.3 km.

The results reported here are also consistent with the radius value reported by Ash *et al.* (1968). Fig. 2 shows that a comparison of the Mariner 5 track with Millstone radar measurements on 19 October gives a bounce radius of 6050.4 km. Fig. 2 is an interesting residuals plot for other reasons since it reveals small systematic differences as well as correlations among the various radars over this time interval.

The radar determinations of the radius of Venus continue to differ significantly from the 6079±3 km value corresponding to the final transmission from Venera 4 that was obtained from matching the Mariner 5 trajectory and occultation information with the atmospheric data from Venera 4 (Kliore and Cain, 1968). In this regard, the Mariner 5 Doppler tracking data during encounter have been used to obtain a Venus-centered trajectory which with the occultation data provides atmospheric information as a function of distance from the center of gravity of the planet. Using the Mariner 5 ranging data alone, one obtains a Venus centered trajectory for Mariner 5 that is virtually identical with the Doppler-only based trajectory. From this, it follows that the Mariner 5 trajectory information is an unlikely source of the disparity between these two values for the radius of Venus. It appears that the Venus radius issue reduces to two propositions: either planetary radar installations in the United States have a systematic bias in time-delay measurements of about +180 μsec or the position of Venera 4 at the instant of its final transmission does not correspond to the Venus radar bounce radius.

[2] Hamilton, T. W. 1968: Earth-based navigational capabilities for planetary missions. Paper presented at the AIAA 2nd Guidance, Control and Flight Dynamics Conference, 13 August, Pasadena, Calif.

[3] Tausworthe, R. C. 1967: Ranging the 1967 Mariner to Venus. Paper No. 36.4, 1967 IEEE Intern. Conf. Record, 20–23 March, New York, N. Y.

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