Reports

The Case for the Radar Radius of Venus

Abstract. *The Venus radius of 6085 ± 10 kilometers, deduced from combining observations made with the Venera 4 and Mariner V space probes is incompatible with the value of 6050 ± 5 kilometers determined from Earth-based radar measurements.*

By comparing data from the space probes of Venera 4 and Mariner V, a value of about 6085 ± 10 km was deduced for the radius of Venus (*1*). (From Venera 4 the temperature and altitude above the surface were obtained, whereas from the Mariner data the temperature was inferred as a function of the distance from center of Venus, the combination yielding the radius.) As the Mariner experimenters pointed out (*1*), their value differs strikingly from the radius of 6056 ± 1 km obtained in mid-1966 from an analysis of Earth-Venus and Earth-Mercury radar data (*2*). We have therefore reanalyzed the radar data, including the new measurements made during late 1966 and 1967. These data were obtained partly with the Millstone Hill and Haystack radars of the M.I.T. Lincoln Laboratory and partly with the radar of Cornell's Arecibo Ionospheric Observatory.

First, we combined all the radar data with the meridian-circle observations made from 1950 to 1965 at the U.S. Naval Observatory and made a weighted-least-squares fit to 23 parameters: 18 initial conditions for the orbits of Mercury, Venus, and the Earth-Moon barycenter; the mass of Mercury and Earth-Moon mass ratio; the light-second equivalent of the astronomical unit; and the equatorial radii of Mercury and Venus (*2*). The rotation of the Earth and the orbits of the Moon and other planets were obtained from standard astronomical sources (*2*) as were the masses of the other planets except for those of the Earth-plus-Moon, Mars, and Venus which were taken from more recent work (*2, 3*). The theory of general relativity was assumed to hold throughout. The result for the radius of Venus was 6050 ± 0.5 km—substantially smaller than our value obtained in 1966. The uncertainty quoted is the formal standard error; a realistic estimate of the uncertainty is probably closer to 5 km. The formal standard error is based on the assumption that all measurement errors are independent and gaussianly distributed with zero means. Thus, possible systematic errors are not allowed for in the computation and the full statistical reductions in the errors implied by "the square root of N" are realized. The same statistical assumptions were also used previously (*2*) and led to the conclusion that "one should only be surprised if future analyses do not yield any parameter estimates differing from ours by more than the formal standard errors" (*4*). Of course, any large systematic errors—unless of a very special sort—would cause correspondingly large systematic trends to appear in the post-fit residuals, whereas none is evident. (Although it is true that a difference in radius, which affects all time-delay measurements equally, is indistinguishable from a fixed delay in the receiver system, the latter has been measured independently to a high precision at each of the three sites.)

Second, we analyzed the Arecibo and the Lincoln data separately and combined each with only the optical observations. The radii obtained were 6052 ± 2 km and 6048 ± 1 km, respectively, and the post-fit residuals showed no systematic trends in either case (Fig. 1 shows the Lincoln Laboratory residuals). The absence of significant residuals indicates that the correct minimum was found in the least-squares analysis.

Finally, we recombined all the data but fixed the radius of Venus at 6075 km to ascertain the extent to which the other parameters of the system could compensate. A portion of the 1967 Earth-Venus time-delay residuals obtained from this computer experiment is shown in Fig. 2. The systematic oscillations in the residuals for 1964 through 1966 have even larger amplitudes. The net result convinces us that the radius of 6085 ± 10 km deduced from the space-probe data is certainly incompatible with our analysis of the radar data. The smaller, systematic differences between the Haystack and Arecibo time-delay measurements, although as yet unexplained, do not alter this conclu-

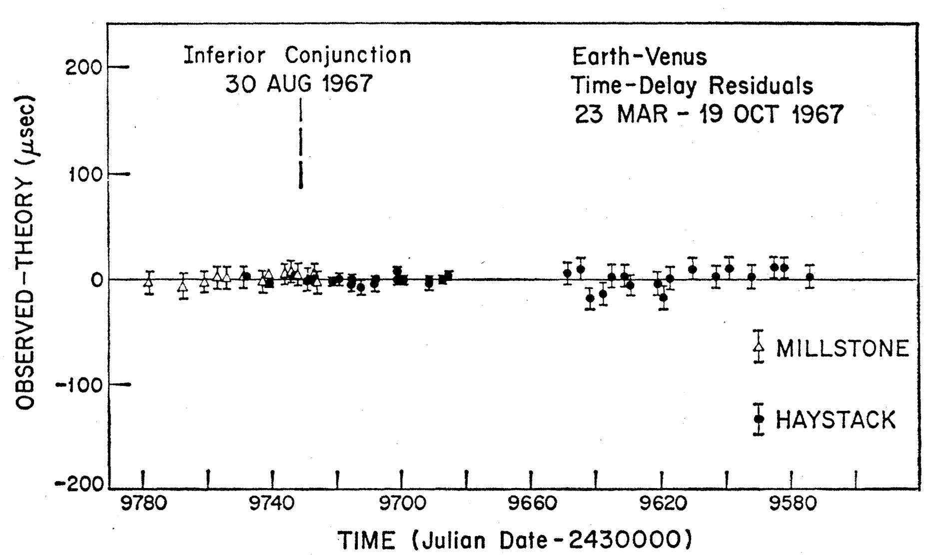

Fig. 1. Representative sample of the post-fit residuals of Earth-Venus time-delay measurements obtained from the Lincoln Laboratory radar data. The estimated radius of Venus was 6048 km.

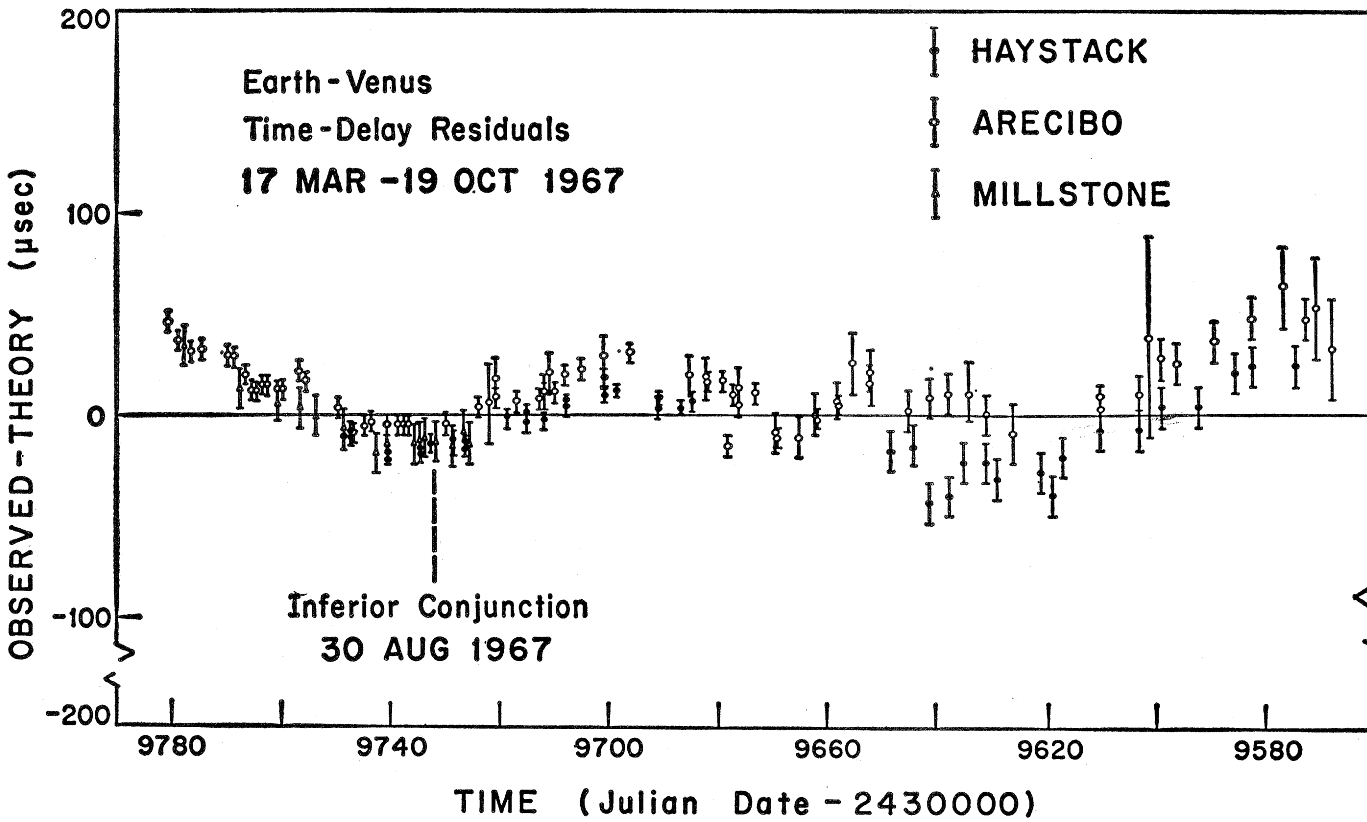

Fig. 2. Sample of the post-fit residuals of Earth-Venus time-delay measurements obtained assuming the radius of Venus to be 6075 km. Fixing the radius at a larger value leads to an even poorer agreement with the radar data.

sion. The slowing down of radar waves in the atmosphere of Venus, which was ignored in our data reduction, has been estimated for rather extreme atmospheric conditions and found to be insignificant in its effect on the radar radius.

Hypotheses regarding topographical effects offer slight promise of resolving the discrepancy. The absence of significant post-fit residuals when the radius is not constrained (for example, Fig. 1) implies that the equatorial region on Venus is remarkably free from large topographical variations. Even the small residuals (< 3 km, one-way) that are present do not seem to represent topographical effects since they do not correlate well with the longitude on Venus. That is, if one regraphs the residuals as a function of the longitude on the planet to which each refers, no significant systematic variations are evident. [However, (i) the resolution cell on the planet's surface of most radar measurements has a linear dimension of the order of 100 km; (ii) the latitude dependence of the observations was ignored since not enough data exist to study the correlations of the residuals simultaneously as a function of both latitude and longitude; and (iii) there will be a tendency, difficult to estimate precisely, for topographical variations of continental dimensions to be masked by offsetting adjustments in the estimates of the other parameters. This last effect may be important because of the slow rotation of Venus and the relatively short time interval spanned by the data.]

The simple possibility that Venera 4 underestimated its altitude by about 35 km cannot yet be ruled out. The scant information available on this altitude determination prompted us to explore the possibility of its being in error. Our approach in essence was to determine whether the extra layer of atmosphere required for agreement with the radar radius could yield a radar cross section for Venus large enough to be consistent with the observations at the 3.8-cm wavelength (*5*). (Since the CO_2-dominated atmosphere absorbs most heavily at the shortest wavelengths, the critical comparison is with these data.) Because of the uncertainties involved in extrapolating the atmospheric parameters and in estimating the absorption coefficient, a definitive answer has not been obtained. Preliminary results, however, indicate that adiabatic atmospheres consistent with the radar radius and the results from Mariner V cannot be constructed without yielding a serious conflict with the observed 3.8-cm radar cross section and angular scattering law (*5*).

It seems possible to obtain reasonable consistency only by increasing the radar radius to about 6060 km or by decreasing correspondingly the estimate of the distance of Mariner V from the center of Venus (*6*). On the other hand, the characteristics of the atmosphere of Venus reported by the U.S.S.R., if applicable to the surface, imply that there is only a relatively small amount ($\approx$ 1 db, two-way) of CO_2-absorption of 3.8-cm waves reflected from the subradar point. In this case, the radar data can be reconciled only by assuming that (i) other atmospheric constituents are present that absorb a significant fraction of 3.8-cm (but not, say, 12-cm) radiation, or (ii) the effective dielectric constant increases with depth leading to a substantially lower radar cross section at 3.8 cm than at wavelengths of 12 cm and higher (*6*), or both. The results from the U.S.S.R. also appear to be inconsistent with the surface temperature inferred from the microwave spectrum (*7*). Calculations, based on this spectrum and on an atmosphere with composition and surface pressure consistent with the U.S.S.R. values, imply a surface temperature of about 675°K (7) rather than 550°K, the value reported by the U.S.S.R. for the surface temperature. An additional source for the microwave emission would be required to achieve consistency. None so far proposed seems plausible.

It is obviously of considerable importance to resolve this question of the radius of Venus not only because of the implications concerning atmospheric and surface conditions, but because the accuracy with which radar and radio observations can be used to test gravitational theories is also thrown into doubt. We await with interest publication of more detailed accounts of the bases for the probe radius of Venus which may provide greater insight into the cause of the present discrepancy.

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References and Notes

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2. For a detailed description of the methods employed, see M. E. Ash, I. I. Shapiro, W. B. Smith, *Astron, J.* **72**, 338 (1967).
3. J. D. Anderson, *JPL Tech. Rep. No. 32-816* (1967); G. W. Null, *Astron. J.* **72**, 1292 (1967).
4. In reference (*2*), the authors were unable to solve simultaneously for all of the unknown parameters because of a limitation of their computer program. Processing these same data after removal of that limitation, Ash, Shapiro, and Smith (January 1967, unpublished) found that the estimate for the radius of Venus decreased to about 6053.5 km. The change from 6055.8 km was caused primarily because the mass of Venus and its radius had not been estimated simultaneously; because of the high correlation (0.6) between the estimates of these two parameters, understandable from Kepler's third law, the radius result obtained from the first analysis was too high by twice the formal standard error of 1.2 km which, of course, did not include the effects of this correlation. The radius value of 6050 km obtained in this paper is based on the spaceprobe mass of Venus (*3*) as well as on additional (1½ years) accurate radar data.
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6. Supporting details will be published separately.
7. W. Ho, I. A. Kaufman, P. Thaddeus, *J. Geophys. Res.* **71**, 5105 (1966).
8. We thank M. Luming and C. Sagan for first calling our attention to the radius controversy. Lincoln Laboratory is operated with support from the U.S. Air Force.

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Radar Determination of the Radius of Venus

Abstract. *The radius of Venus has been determined from radar-range data taken at the Jet Propulsion Laboratory's Goldstone facility. A simultaneous integration of the equations of motion of the solar-system fit to this time-delay data gave a value of 6053.7 ± 2.2 kilometers. A discussion of other Venusian radius determinations is made.*

A determination of the radius of Venus and the astronomical unit has been made with planetary radar data from the Jet Propulsion Laboratory. The value of the radius is discordant with an estimate of the radius of the Venusian surface which was inferred from an analysis of atmospheric data obtained with the Soviet Venera 4 space probe in conjunction with the differential Doppler-frequency shifts on the radio signals of the United States space probe Mariner V during its occultation by Venus (*1*).

The Soviet probe obtained *in situ* measurements of the composition, temperature, pressure, and density during its parachute descent which were related to altitude from the known aerodynamic characteristics of the parachute and a single radar altimeter mark obtained at a height of 26 km above the radar reflecting surface (*2*). The pressure and temperature values from Mariner V occultation overlap those from Venera 4 at the position of its 26-km radio altimeter mark. Since the Mariner V atmospheric parameters were known as a function of the distance to the center of Venus from the trajectory analysis and the corresponding Venera 4 parameters at 26 km above the surface, an estimate of the Venusian radius of 6080 ± 10 km has been inferred (*1*).

The above value of the radius is in serious disagreement with that obtained at the Lincoln Laboratory from Earth-based radar time-delay measurements (*3*). A value of 6056 ± 1.2 km was obtained (at Lincoln) in a multi-parameter least-squares analysis of Venus and Mercury radar range data and meridian circle observations of the same planets and the Sun made at the U.S. Naval Observatory.

We have carried out a similar analysis of radar time-delay measurements to Venus from a single radar system at the Jet Propulsion Laboratory's Goldstone facility (*4*). The observations span the period from May 1964 to October 1967. Our results are in close agreement with those reported in reference (*3*). The observations of 1964–1966 and in 1967 are reported in references (*5*) and (*6*), respectively. None of the observations discussed here were used in the work of reference (*3*), and consequently, this represents an entirely independent data source. The previous work used observations from different radar facilities, all operating at frequencies considerably lower than that of the JPL radar which is 2388 Mhz. This frequency is sufficiently high so that the ionosphere and the interplanetary electron plasma effects are essentially negligible in our observations.

Estimates of the orbital parameters, the astronomical unit, and the radius of Venus were obtained with a differential correction technique which adjusts initial conditions (the parameter) in a numerical integration of the solar system n-body differential equations of motion. The equations included the effects of general relativity, although they are unimportant for this discussion. The masses used in the integration are those specified in reference (*7*). Since only radar observations of Venus were used, it was necessary to limit the parameter set to only those parameters that are sensitive to time-delay measurements, for example, parameters defining the orientation of Earth's orbit