The Case for the Radar Radius of Venus

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ABSTRACT

The 6085±10 km radius of Venus deduced from combining observations made with the Venera 4 and Mariner 5 space probes appears to be incompatible with the 6050±5 km radius determined from earth-based radar measurements.

1. Introduction

Data from the Venera 4 and Mariner 5 space probes were judged (Snyder, 1967; Kliore *et al.*, 1967) to be consistent only if a value of about 6085±10 km was assumed for the radius of Venus. (From Venera 4 the atmospheric temperature and pressure were reported as a function of altitude above the surface, whereas from the Mariner data the temperature and pressure were inferred as a function of the distance from Venus' center, the combination yielding the radius.) As the Mariner experimenters pointed out, their value differs strikingly from the 6056±1 km radius obtained in mid-1966 from an analysis of Earth-Venus and Earth-Mercury radar data (Ash *et al.*, 1967). We have therefore reanalyzed the radar data, including the new measurements made during late 1966 and 1967 (Ash *et al.*, 1968). 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.

2. Reanalysis of radar data

The mean radius of Venus can be determined from the radar time-delay data because its effect, unlike that of all the other initially unknown parameters, is time independent. (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 to high precision independently at each of the three sites.) Because some of the recent individual time-delay measurements have uncertainties of only 3–10 μsec, equivalent to 0.5–1.5 km error in distance, the radius can be determined with comparably high accuracy.

The purpose of our new analysis was twofold: first, to obtain a current estimate for the radius by including the new, highly accurate data; and second, to ascertain the degree of incompatibility of the radius value of 6085 km with the planetary radar data.

First, we combined all the radar data with the U. S. Naval Observatory's meridian-circle observations from 1950–1965 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 the earth-moon mass ratio; the light-second equivalent of the astronomical unit; and the equatorial radii of Mercury and Venus (Ash *et al.*, 1967). The rotation of the earth and the orbits of the moon and the other planets were obtained from standard astronomical sources as were the masses of the other planets except for those of earth-plus-moon, Mars, and Venus, which were taken from more recent work (Ash *et al.*, 1967; Anderson, 1967; Null, 1967). 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 1966 value. 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 uncertainty in the deduced radius is computed as though the full statistical reductions in the errors implied by "the square root of N" were realized. The same statistical assumptions were also used previously (Ash *et al.*,

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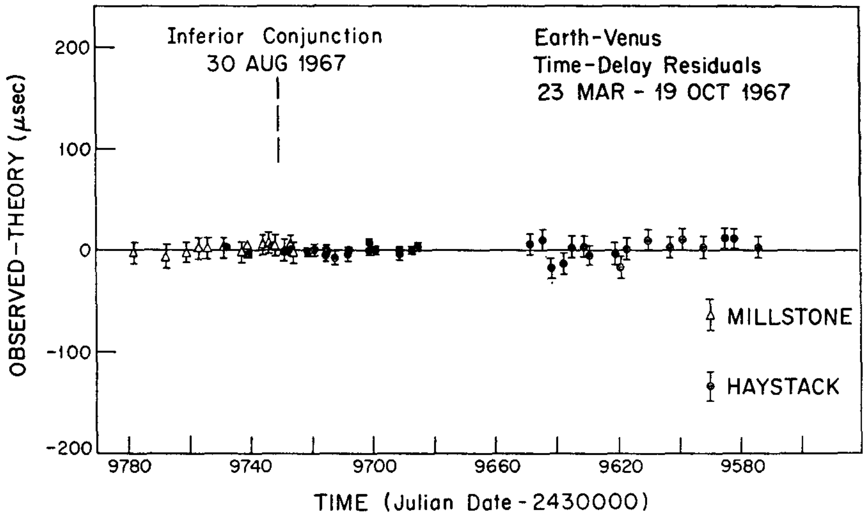

FIG. 1. Representative sample of the post-fit residuals of Earth-Venus time-delay measurements obtained from the Lincoln Laboratory radar data. The estimated radius of Venus was 6048 km.

1967) and led those authors to conclude 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."[3] 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. In addition, we analyzed the Arecibo and the Lincoln data separately, combining each with only the optical observations. The radii obtained were 6052±2 and 6048±1 km, respectively and the post-fit residuals showed no systematic trends in either case (see, for example, Fig. 1). The absence of significant residuals indicates that the correct minimum was found in the least-squares analysis.

Second, 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 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 conclusion. The slowing down of radar waves in the Venus atmosphere, 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 scant promise of resolving the discrepancy. The absence of significant post-fit residuals when the radius is not constrained (see, 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 appear to 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. [Note, however: 1) the resolution cell on the planet's surface of most radar time-delay measurements has a linear dimension of the order of 100 km; 2) 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 3) 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.]

3. Effect of possible Mariner 5 or Venera 4 errors

Having adduced the evidence for the radar radius of about 6050 km, we are prompted to explore briefly the possibilities that either Mariner 5 overestimated its dis-

[3] Note also that Ash *et al.* (1967) 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 *et al.* (unpublished, January 1967) found that the estimate for the radius of Venus decreased to about 6053.5 km. The change from 6055.8 km was caused primarily by the mass of Venus and its radius not having 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 space-probe mass of Venus (Anderson, 1967) as well as on an additional $1\frac{1}{2}$ yr of accurate radar data.

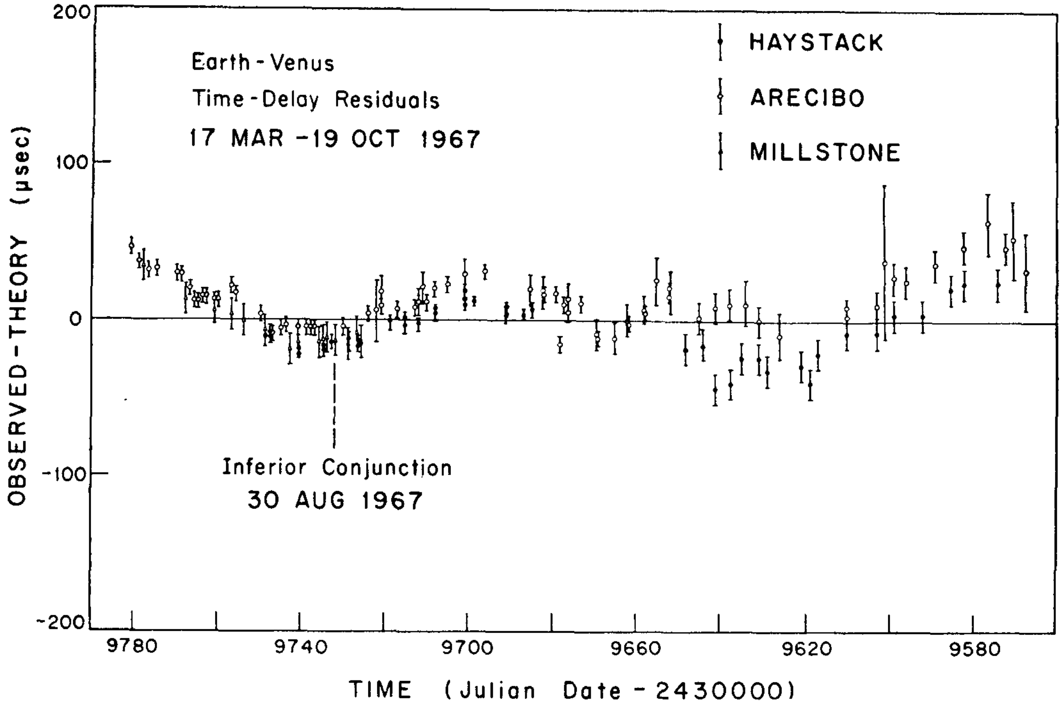

FIG. 2. Sample of the post-fit residuals of Earth-Venus time-delay measurements obtained assuming the radius of Venus to be 6075 km. Fixing the radius at a larger value leads to an even poorer agreement with the radar data.

tance from the planet's center by perhaps 10 km,[4] or Venera 4 underestimated its altitude by about 35 km. In evaluating each of these two possibilities an additional effect, molecular absorption of radio waves in a dense CO_2 atmosphere, will be used as the principal criterion. Since such an atmosphere absorbs most heavily at short wavelengths, the critical comparison is thus with the 3.6–3.8 cm wavelength radar data; the smaller (possible) absorption at 12.6 cm would have similar but less significant effects upon the radar cross section, and upon radio brightness data (Evans, 1968). [The apparent radar cross section of Venus has been measured to be about 1% at 3.6 cm (Karp *et al.*, 1964) and at 3.8 cm (Evans *et al.*, 1966; Evans, 1968), in contrast with the value of about 15% observed at several longer wavelengths; the difference has been attributed, though not definitively, to atmospheric absorption.] Because of the uncertainties involved in extrapolating the atmospheric parameters and in estimating the absorption coefficient (Ho *et al.*, 1966), a definitive answer has not been obtained. Preliminary results, however, indicate that adiabatic atmospheres consistent with the radar radius and the Mariner 5 results cannot be constructed without yielding a very large 3.6-cm optical depth, in obvious conflict with the observed radar cross section and with the angular scattering law (Evans *et al.*, 1966). It seems possible to obtain reasonable consistency only by increasing the radar radius to about 6060 km or by decreasing correspondingly the estimate of Mariner 5's distance from the center of Venus.[4] In either case the well known curve [see, for example, Barrett and Staelin (1964)] of radio brightness temperature vs wavelength must be reinterpreted theoretically, considering the effects of very high surface pressures and temperatures.

On the other hand, the characteristics of the Venus atmosphere reported by the U.S.S.R., if applicable to the surface, imply that there is only a relatively small amount (≈ 1 db, two-way) of CO_2 absorption of 3.6-cm radar waves. In this case, the radar data can be reconciled only by assuming other atmospheric constituents are present that absorb a significant fraction of 3.6-cm (but not, say, 12-cm) radiation and/or the effective dielectric constant may increase with depth, leading to a substantially lower radar cross section at 3.6 cm than at wavelengths of 12 cm and higher (Evans, 1968). However, accepting the surface temperature of 553K reported by Venera 4 experimenters would require, in addition, an explanation for the origin of the much higher radio brightness temperature of Venus and its wavelength dependence. The possibility that the Venera 4 spacecraft landed on an extremely high mountain peak seems remote in view of the lack of discernable topography found in the analysis of the radar data.

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

[4] *Note added in proof.* The distance, from the center of Venus, of the ray path from Mariner 5 to the earth has, in fact, recently been adjusted downward by about 6 km (Kliore and Gain, 1968).

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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