mosphere 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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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 Processing these same data after removal of that limitation, Ash, Shapiro, and Smith (January 1967, unpublished) found that the estimate for the radius of Venus decreased to about 6053.5 km.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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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.

14 March 1968; augmented 30 April 1968

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

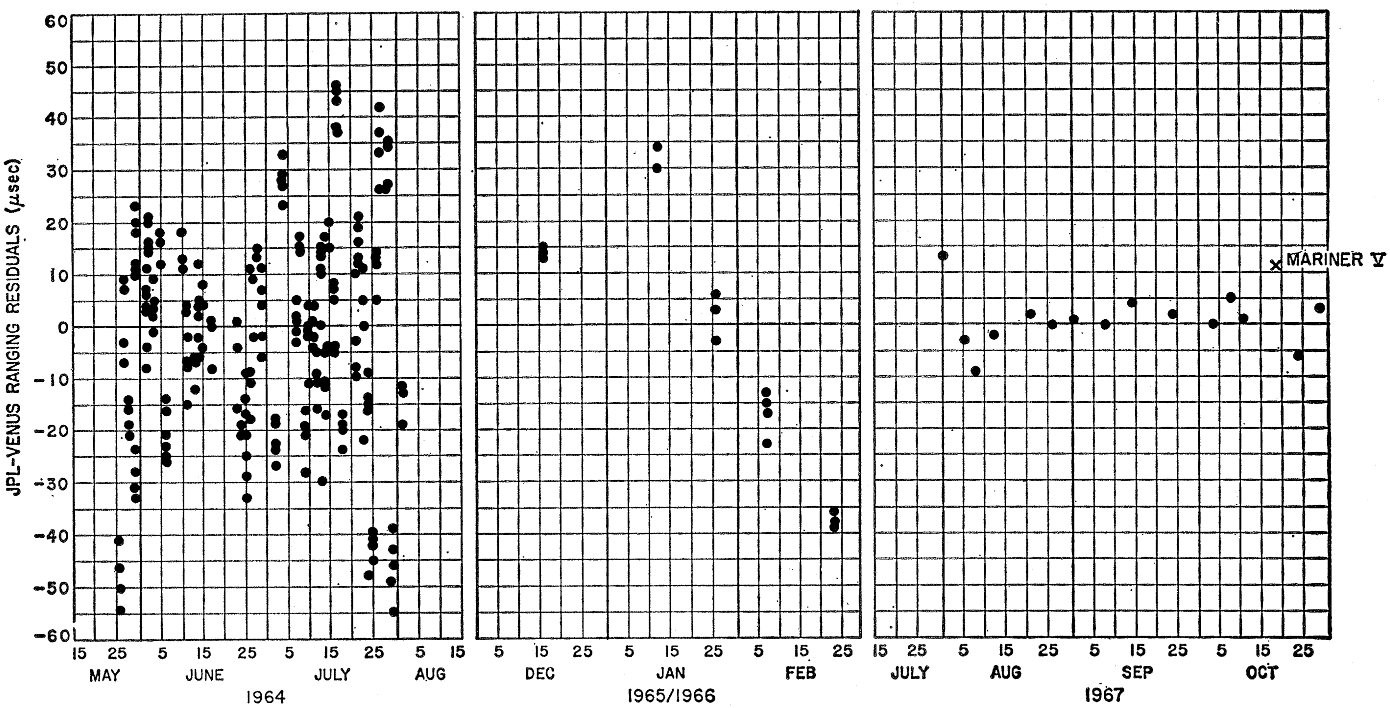

Fig. 1. Residuals for JPL radar range after an orbit correction and for the independent determination of the center of gravity of Venus from Mariner V.

relative to the astronomical right ascension and declination coordinate system were not adjusted. In all, ten parameters were corrected. In a Keplerian context, these correspond to: two parameters determining the orientation of the Venusian orbital plane relative to the ecliptic, the longitude of Venus relative to that of Earth at the initial epoch, the eccentricities and perihelion longitude of Venus and Earth, the semimajor axis of Earth (*8*), the light time for 1 astronomical unit (A.U.), and the radius of Venus. The radius of Venus can be determined in this way since it enters linearly in the ephemeris computation of the comparison observables, namely, a change in the radius of 1 km causes a change in the range of 6 μsec independently from the position of the planets in their orbits. If any time delay bias exists in the radar system, it will be absorbed in the radius estimate. Thus, the value of a determination from an independent data source is obvious.

The numerical results for the orbital parameters are not reported here, since only their effects on the radius determination needed to be removed. The resulting value of the radius of Venus is 6053.7 $\pm$ 2.2 km. It is important to note that this value is conditional on the figure and topography of Venus in the radar echo zones corresponding to the observation intervals. An additional parameter of interest is the astronomical unit. The resulting value is 149,597,892.9 $\pm$ 5 km, which was expressed in kilometers by multiplying the light time for 1 A.U. by an adopted speed of light, 299,792.5 km/sec. The corresponding value obtained from the work of reference (*3*) is 149,597,892.3 $\pm$ 1 km. The agreement in these two estimates is remarkable. The residuals from the final fit (observed minus computed) are shown in Fig. 1. The vast improvement in measurement accuracy with time is clearly shown, the root-mean-square deviation of the 1967 data being about 4 μsec ($\sim$ 1 part in 10^8). Some systematic effects remain in 1964 and 1966 residuals; these may be due to topographic features on Venus, second-order effects of the fixed parameters, or systematic measurement errors (*9*).

Complete computations with all available planetary radar observations from JPL, M.I.T., and Arecibo, and with U.S. Naval Observatory Meridian Circle observations of the Sun and major planets have been carried out, but are not ready for publication. The values of the radius and the astronomical units obtained from our limited data set agree to within the stated standard deviations with the results from the complete data set.

The strong independence of our results from those of Ash, Shapiro, and Smith (*3*) should be emphasized. No observations were used in common in both computations. Furthermore, all computational equations and procedures are completely independent including the *n*-body integration, computation of observables, parameter sets, and least-squares analysis. The consistency of the radar results is strong and the inconsistency with the radius inferred from the Venera 4 and Mariner V measurements is significant.

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3. M. E. Ash, I. I. Shapiro, W. B. Smith, *Astron. J.* **72**, 338 (1967).
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8. Solving for the semimajor axis of the orbits of both planets simultaneously leads, in the pure radar solution, to a near-singular normal matrix. The dominant signature in the time delay observable, resulting from adjusting the semimajor axis, is due to the change in the mean motion of the planet rather than to the direct effect of the change in the semimajor axis itself. The orbits of Venus and Earth are nearly coplanar and circular; so a change in the mean motion of Venus is almost indistinguishable from a corresponding negative change in the mean motion of Earth. The choice of either semimajor axis accommodates the relative mean motion correction and gives essentially the same results for the other parameters. In this solution, the semimajor axis of the Earth-Moon barycenter was used because it gave a slightly better fit in the least-squares sense.
9. The Mariner V spacecraft ranging and counted Doppler data taken during the Venus encounter phase provide an important and independent determination of the position of the center of gravity of Venus. The preliminary residual from Mariner V data analysis is shown on this figure at the epoch of closest approach to Venus, 19 October 1967 (private communications from J. D. Anderson, JPL).

10. This report presents the results of one phase of research carried out at the Jet Propulsion Laboratory, California Institute of Technology, under NASA contract NAS 7-100.

1 April 1968

Old Faithful: A Physical Model

Abstract. *The recent confirmation of a prediction that relates the duration of eruption to time between eruptions suggests a physical model of the internal cavity of Old Faithful.*

Rinehart (*1*) has proposed that Old Faithful exhibits two modes of eruption. One mode (a long interval between eruptions) consists of a 20- to 30-minute quiet period and is concluded by a brief series of long-period ground movements that are followed by general seismic activity (weak tremors and strong pulses) that continue up to the time of eruption. The second mode (a short interval between eruptions) is characterized by immediate seismic activity, consisting of both weak tremors and strong pulses and occasionally including the introductory long-duration movements. This activity continues up to eruption. There is no observable relationship between long and short intervals between eruptions. Old Faithful has also been observed to exhibit a range of from 1.5 to 4.5 minutes in the duration of water play.

On the basis of these data (*1*), I proposed (*2*) that Old Faithful consists of a single cavity that occasionally was incompletely emptied in an eruption. If we make the assumption that seismic activity is related to the boiling activity in the geyser cavity, we can explain (i) the immediate onset of seismic activity (in cases of a short interval between eruptions) and (ii) the existence of short-interval eruptions, by hypothesizing that this mode of eruption results when the prior eruption incompletely evacuates the cavity, and hence the cavity remains partially full of hot liquid. Therefore, there would be immediate boiling activity, and less time would be necessary to reach the critical point for a second eruption.

In cases of complete eruption, the cavity is left essentially empty, and there would follow a longer interval preceding the next eruption. The first part of this period would be quiet because there would not already be a mass of hot boiling liquid in the cavity. On the basis of the above rationale, I proposed that the relation between duration of water play (this should provide an estimate of how completely the cavity is emptied) and the length of the interval to the subsequent eruption should be examined, and I hypothesized that a brief duration of water play (incomplete emptying) would be associated with a brief interval to the following eruption.

This hypothesis was tested by Rinehart and confirmed (*3*); its confirmation suggests that there is a physical model for the geyser cavity (Fig. 1). During the quiet portion of a long interval between eruptions, the lower U part of the cavity would slowly fill and come to a boil. Seismic activity would result when the mass of boiling water was great enough to seal off the U portion of the cavity. This would mean that venting steam from the back half of the cavity would have to blow out through the water mass, producing detectable vibrations. An eruption would take place when the U portion of the cavity was sufficiently full to splash a quantity of water over into the hot, dry, back half of the cavity. The water would immediately flash boil to steam, forcing the water out of the U section of the cavity. The extent of the eruption would depend on the quantity of water splashed into the back half of the cavity. A large splash would generate a large volume of steam and blow the cavity clean. A smaller splash would result in a partial evacuation of the cavity. If, in the latter event, sufficient water remained in the cavity to seal off the U portion of the cavity, new seismic activity would start immediately.

Data on the volume of water erupted would provide an additional test of the model. Because the geyser opening is a constant, a measure of the velocity of the escaping liquid in addition to the duration of water play would provide a good estimate of the volume ejected. On the basis of the above model, one would predict that eruptions which precede a long interval (complete emptying) would involve longer water play, a greater total volume ejected, and also a greater water eruption velocity. (It has been hypothesized above that a greater volume of steam is generated in these cases.) Therefore the internal pressure should be greater, and

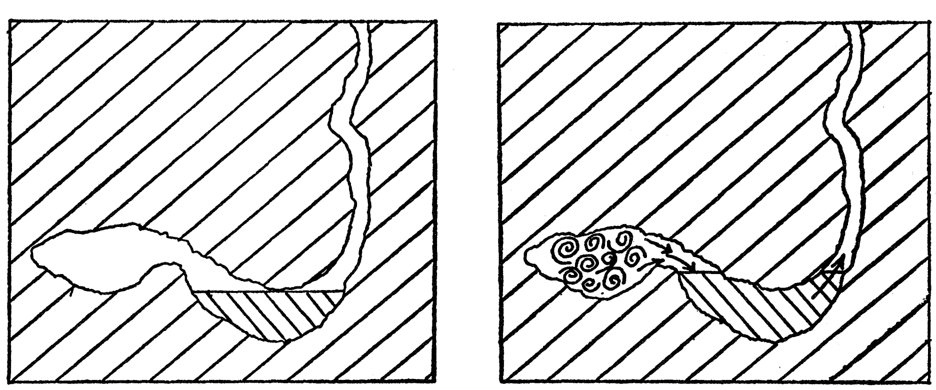

Fig. 1. (Left) Cavity filled to point at which the surging motion of the water in the U portion of the cavity (which results from the venting of steam from the back portion) would produce noticeable ground tremors and pulses. (Right) Water splashing over into the hot, dry, back portion of the cavity flashes into steam and blows the liquid up and out of the U portion of the cavity.