Venus: Topography Revealed by Radar Data

Abstract. *Surface height variations over the entire equatorial region on Venus have been estimated from extended series of measurements of interplanetary radar echo delays. Most notable is a mountainous section of about 3-kilometer peak height located at a longitude of 100 degrees (International Astronomical Union coordinate system). The eastern edge has an average inclination of about 0.5 degrees, which is unusually steep for a large-scale slope on Venus. The resolution of the radar measurements along the surface of Venus varied between about 200 and 400 kilometers with a repeatability in altitude determination generally between 200 and 500 meters. The mean equatorial radius was found to be 6050.0 ± 0.5 kilometers.*

The surface of Venus can be studied from afar only with radio waves. For the past decade interplanetary radar measurements of ever-increasing precision have been made of the round-trip echo delays of signals transmitted from the earth toward Venus. During the most recent inferior conjunction in November 1970 the errors in the measurements of delay were no more than 1 μsec—about a thousandfold improvement compared with the earliest such data obtained in 1961. From the newer observations we have been able to extract values for surface height variations over the entire equatorial region on Venus. These results form the basis for this report.

In principle, surface heights are simple to determine. Given the orbits of both the earth and Venus, a time-delay measurement can be interpreted directly in terms of the average altitude of the reflecting area that contributes to the echo. The size of the area depends on the effective extent of the pulses of radio energy and on the scattering law of the surface (*1*). This approach is complicated by two factors: (i) the orbits of the earth and Venus must be determined from the very data that are to be used for the inference of surface heights; and, relatedly, (ii) the spin of Venus is synchronous, or nearly so, with the relative orbital motion of the earth and Venus (*2*). The latter fact makes the separation of surface and orbital effects more difficult than, for example, with radar observations of Mars (*3*). Nonetheless, since Venus completes four rotations on its axis, as seen by an observer on the earth, between successive inferior conjunctions, topographic effects, which nearly repeat for each rotation, tend to be distinguishable from orbital ones. The distinction is not completely straightforward because the latitude of the subearth point does not repeat exactly with the longitude, particularly near inferior conjunction where the greatest precision is possible. Variations of surface height with small changes in latitude therefore distort the interpretation. The nearly commensurate 13:8 ratio of the orbital periods of the earth and Venus insures that in each 8-year cycle the subradar point traces out virtually the same path on Venus's surface. This near periodicity is also a complicating factor. But, with patience, a complete separation of topographic from orbital effects will be possible since, presumably, the time scale for physical change in surface structure is usefully measured in units far longer than decades.

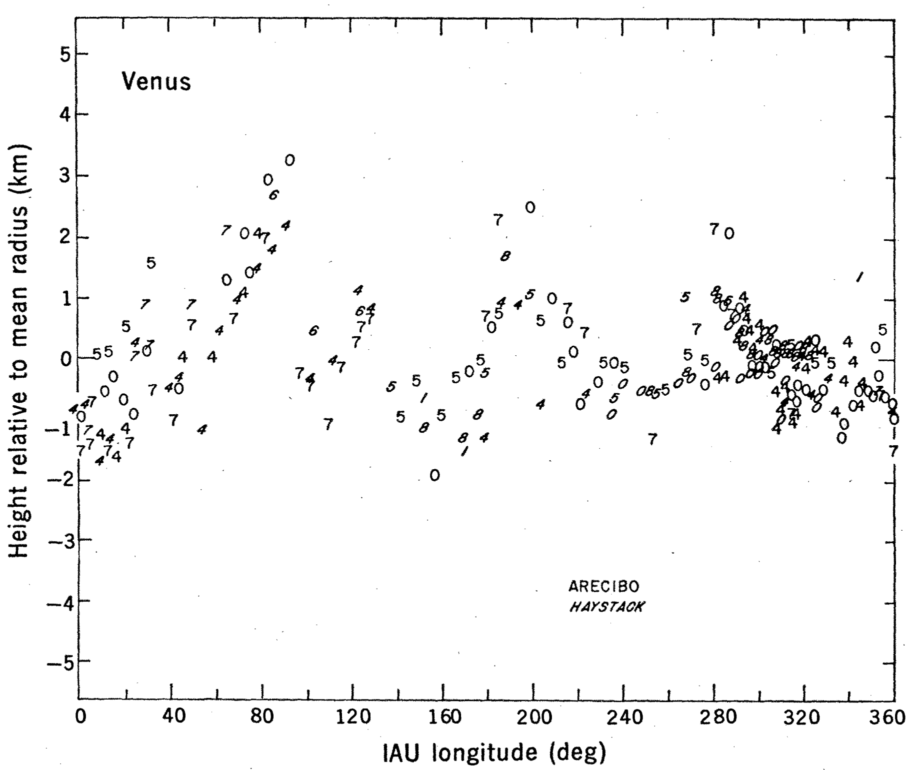

Fig. 1. Surface-height variations over the equatorial region on Venus inferred from radar echo-delay measurements. The data were obtained at radar frequencies of 430 and 7840 Mhz at the Arecibo and Haystack observatories, respectively. The longitude scale is based on the IAU system (*8*). The times of the observations are coded by the number of axial rotations made by Venus as seen from the earth; the epoch is the late-August 1967 inferior conjunction, and the final data are from the November 1970 inferior conjunction. During this period the latitudes of the subearth points on Venus varied from about −9° to +10°. All the data points have standard deviations under 7 μsec; the most recent (eighth revolution) data have typical standard errors of 1 μsec. The reference level is the mean equatorial radius, estimated to be 6050.0 ± 0.5 km after correction for the small effect of retardation in Venus's atmosphere.

To achieve this separation with the present limited data span, we utilized several techniques. First, we simply ignored topography and used the earth-Venus and other radar data simultaneously to solve for the maximum-likelihood estimates of the relevant orbital initial conditions of the four inner planets, a single average radius for each of these planets (except the earth), and several other necessary astronomical constants (*4*). All told, the values for 23 parameters were obtained. The data were from both the Massachusetts Institute of Technology's Haystack Observatory and Cornell's Arecibo Observatory (now the National Astronomy and Ionosphere Center). The post-fit residuals from the earth-Venus data, as a function of the longitude and latitude of the subradar point, were taken to represent the surface height variations on Venus with respect to its mean equatorial radius.

As a second approach, we used a spherical-harmonic expansion to represent the topography of Venus and the other target planets and estimated the low order (primarily sectorial) coefficients. In a variation on this technique, we substituted a double Fourier series to represent the planetary surface-height variations (*5*).

The results from these two analyses and minor variants thereof were very similar. Good consistency was obtained between Haystack and Arecibo data (*6*) and for both sets between one conjunction and the next. The estimates for the mean equatorial radius all fell within the limits 6050.0 ± 0.5 km, in excellent agreement with our previous result (*7*), which was based on fewer observations. For the 23-parameter solution, the surface heights relative to this radius are shown in Fig. 1 as a function of the International Astronomical Union (IAU) longitude (*8*) of the subearth point. The data are distinguished by synodic rotation number—the number of rotations of Venus as seen by an observer on the earth—starting with zero at the inferior conjunction of late August 1967 and continuing through the corresponding conjunction of November 1970. The standard error associated with each measurement was omitted so as to prevent obscuration of the similarities and differences among the residuals. All of these errors were under 7 μsec, with the Haystack data having uncertainties in delay of no more than 1 μsec (equivalent to 150 m uncertainty in surface height) near the last inferior conjunction. The regions on the surface to which the average heights apply range in size from about 200 to 400 km (*1*). The repeatability of the results for different rotations is an indication of their reliability and a measure of the success of our separation of the topographic from orbital effects (*9*). This internal consistency for most longitude regions appears to be within about 200 to 500 m. Because of the variations in the latitude on Venus to which data points from successive rotations refer, and because of the decreased accuracy associated with the measurements further from the inferior conjunctions, it is difficult to place more precise bounds on the uncertainties of the surface heights shown in Fig. 1.

The latitudes of the subearth points on Venus exhibit the largest excursions near inferior conjunctions. For the three conjunctions represented in Fig. 1, these latitudes were, chronologically, about 10°, −9°, and 5°. Some latitude dependence can be seen in the topography, but the most striking feature is the 3-km-high peak at about 100° longitude. This feature seems to rise gently from the west (smaller longitudes) with a slope of about 0.04 degree, but it then drops precipitously to the east with a slope perhaps as large as 0.5 degree. More closely spaced observations in the longitude region between about 90° and 110° are required in order to determine the true shape of the eastern slope. The extent of this elevated region is at least 500 km in latitude and about 6000 km in longitude. Its existence was even apparent in the data at much lower resolution reported earlier (*10*). Other, shallower peaks and valleys are clearly evident in Fig. 1 (*11*). Higher, sharper peaks may also be present but would not be visible because the data in the figure generally represent averages over large regions. One very narrow peak, about 1.5 km in altitude, has in fact already been observed by a different method (*10*).

What are the prospects for improvement in the surface resolution and in the accuracy of the altitude determinations? Near inferior conjunction, the main limitation is placed not by the signal-to-noise ratio but by the effective pulse length, Δt (*1*). For Haystack, and similarly for Arecibo, relatively straightforward modifications would make it possible for phase codes with Δt's of 1 μsec to be transmitted and the echoes analyzed. The corresponding surface-area resolution cell would be about 50 km in radius; the height resolution for strong signals might be as fine as 30 m. As the surface resolution improves, the frequency of obtaining closure observations (that is, multiple measurements of the same surface cell but from different relative orbital positions) will perforce decrease—until the surface heights, on a scale corresponding to the precision of the echo-delay determination, begin to be well correlated over distances that exceed the surface resolution of the measurements. Although this improvement reduces the number of strict closure points obtained in a given observation interval, the weight of those available may more than compensate in the separation of orbital and topographic effects. An even more promising solution is to use methods in which a relatively large portion of the planet's topography is determined simultaneously with little loss in resolution. One such technique (*12*) provides from 1 day's measurements fine resolution along an extended portion of the apparent Doppler equator. The newer method of delay-Doppler interferometry (*13*) will allow the topographic determinations to be extended away from the equatorial regions but with increasingly poorer resolution. The latter technique utilizes the delay, Doppler, and fringe-phase measurements to provide three-dimensional maps of a planetary surface. For useful accuracies, more sensitive radar systems such as the new Goldstone radar (*14*) and the soon-to-be-improved Arecibo radar (*15*) must be used.

The present results, although limited, show that Venus has a rich, varied, and durable topography, its high surface temperature of 800°K notwithstanding. The degree to which isostatic compensation may take place, however, cannot be determined reliably until detailed gravity data become available.

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References and Notes

1. In all current time-delay measurements, a phase-coded waveform is transmitted; in the present work, the constant-phase intervals (or baud lengths) varied from 6 to 60 μsec. The extent in time of the code element, Δt, determines the effective resolution area, ΔA, on the surface through the simple formula

$$\Delta A \simeq \pi R c \Delta t$$

where c is the speed of light and R is the planet's radius. This result depends on the surface being nearly spherical and on the scattering law being nearly constant in the vicinity of the subradar point. Under these assumptions, the resolution cell on the surface of Venus ($R \simeq 6050$ km) will have a diameter of about 300 km for $\Delta t \simeq 10$ μsec. If the echo power falls off significantly with increased separation of the reflecting region from the subradar point, as is normally the case, then the effective resolution at the subearth point is perforce improved. The precision of the determination of average altitude is also proportional to Δt and, in most cases of interest, is nearly inversely proportional to the signal-to-noise ratio. Further details on the applications of phase-coded waveforms to radar astronomy and the role of the scattering law are provided by G. H. Pettengill, in *Radar Handbook*, M. Skolnik, Ed. (McGraw-Hill, New York, 1970), chap. 33.
2. See, for example, R. M. Goldstein, in *Moon and Planets*, A. Dollfus, Ed. (North-Holland, Amsterdam, 1967), p. 126; I. I. Shapiro, *Science* **157**, 423 (1967); R. F. Jurgens, *Radio Sci.* **5**, 435 (1970); R. L. Carpenter, *Astron. J.* **75**, 61 (1970).
3. G. H. Pettengill, A. E. E. Rogers, I. I. Shapiro, *Science* **174**, 1321 (1971); A E. E. Rogers, M. E. Ash, C. C. Counselman, I. I. Shapiro, G. H. Pettengill, *Radio Sci.* **5**, 465 (1970); R. M. Goldstein, W. G. Melbourne,

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4. The radar data are relatively insensitive to the values of the "out-of-plane" orbital parameters, which can therefore be fixed in accord with the results from optical observations of the planets without the concomitant errors introducing a significant distortion into the altitude determinations. A detailed description of the methods used to obtain the estimates of the other parameters can be found in M. E. Ash, I. I. Shapiro, W. B. Smith, *Astron. J.* **72**, 338 (1967). See also I. I. Shapiro, M. E. Ash, R. P. Ingalls, W. B. Smith, D. B. Campbell, R. B. Dyce, R. F. Jurgens, G H Pettengill, *Phys. Rev. Lett.* **26**, 1132 (1971).
5. Another technique, currently being tested, involves the use of only data corresponding to longtitude-latitude resolution cells that were observed from widely separated orbital positions. By the addition of one radius parameter for each such cell, the separation of orbital and topographic effects can be achieved. With the orbits thus obtained, all of the data can be interpreted directly in terms of surface heights. Difficulties with this approach include the effects of (i) omission of a large fraction of the data in the orbit-determination process and (ii) differences in the exact subearth point for data assigned to the same resolution cell.
6. In fact, in some of the computer experiments a parameter representing the "bias" of the Arecibo data relative to Haystack's was added; the estimate for this parameter was always under 1 μsec, which is equivalent to a bias in radius of under 150 m.
7. M. E. Ash, D. B. Campbell, R. B. Dyce, R. P. Ingalls, R. Jurgens, G H. Pettengill, I. I. Shapiro, M. A. Slade, W. B. Smith, T. W. Thompson, *Science* **160**, 985 (1968).
8. At its last general assembly in 1970, the IAU proposed a standard value for the rotation vector of Venus that is consistent with current knowledge. The precise definition is given in *Proceedings of the 14th General Assembly of the International Astronomical Union* (Reidel, Dordrecht, 1971), p. 128. The central meridian on Venus, as seen from the center of the earth at 0 hour, universal time, on 20 June 1964, is 320° in this system and increases with time. The assumed inertial spin period is 243.0 days (retrograde), which is slightly less than the synchronous period of 243.16 days. Partly because of this difference, the data in Fig. 1 are not plotted in exact accord with the IAU system; they are displaced toward smaller longitudes, but nowhere by more than a few degrees.
9. The number of orbital degrees of freedom is not overwhelmingly large. For Venus, only the four in-plane parameters are relevant [see (*4*)]; for the earth, the corresponding orbital elements are also constrained by the radar observations of Mercury and Mars. Thus, of the 23 parameters involved in the solution, relatively few are more than minimally correlated with the topography estimates. This conclusion is verified by the results from solutions in which topography parameters were estimated explicitly (see text).
10. W. B. Smith, R. P. Ingalls, I. I. Shapiro, M. E. Ash, *Radio Sci.* **5**, 411 (1970).
11. For example, note the modest (1 km) near-equatorial rise at 280° longitude.
12. R. P. Ingalls and L. P. Rainville, in preparation; see also (*10*).
13. I. I. Shapiro, M. A. Slade, A. E. E. Rogers, S. H. Zisk, T. W. Thompson, in preparation.
14. The sensitivity of this radar (R. M. Goldstein, personal communication) is about 50 times that of Arecibo, and of Haystack when the latter is observing Venus. Venus's thick CO_2 atmosphere absorbs Haystack's X-band radiation and thereby reduces the echo power by a factor of about 6 relative to the echoes from the Goldstone and Arecibo signals, which are at substantially lower radio frequencies.
15. F. D. Drake, personal communication.
16. We thank M. E. Ash, R. Cappallo, R. F. Jurgens, and W. B. Smith for their vital contributions to earlier phases of this study and the staffs of the Haystack Observatory and the National Astronomy and Ionosphere Center for their aid in performing the radar experiments. Research at the Haystack Observatory is supported by NSF grant GP-25865 and NASA grant NGR22-174-003; contract NAS9-7830. The National Astronomy and Ionosphere Center is operated by Cornell University under a contract with the National Science Foundation.

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Visibility and Soiling: A Comparison of the Effects of Leaded and Unleaded Gasolines

Abstract. *The emissions from a fleet of late-model cars fueled with commercial, high-aromatic, unleaded gasoline caused nearly twice as much atmospheric light extinction as those from a matched fleet fueled with commercial, low-aromatic, leaded gasoline, when both were driven according to a consumer operating cycle in an idle traffic tunnel. The increased extinction and greater soiling potential result mainly from greater light absorption by the air-suspended particles from the unleaded fleet.*

It has been postulated that atmospheric clarity (*1*) might be improved if unleaded rather than leaded gasoline were used, because the light-scattering particles of lead compounds would be absent from the exhaust (*2*). On the other hand, calculations based on measurements of the mass of aerosol particles emitted from dynamometer-driven cars have shown greater volumes of exhaust particles from unleaded than from leaded gasoline during consumer-type mileage accumulations (*3*), a result which suggests that the use of unleaded fuel could result in reduced, rather than improved, atmospheric visibility. In tests designed to test this inference, the diluted exhaust of dynamometer-driven 1970 cars burning leaded and unleaded versions of two gasoline blends, each having an aromatic content of either 24 or 55 percent (by volume), showed greater light scattering and soiling in the absence of lead additives at the low, as well as the high, aromatic concentration (*4*).

Maintenance of octane quality at levels satisfactory for most cars now on the road, under realistic schedules for the rapid removal of lead antiknock compounds from commercial gasoline, would demand an appreciable increase in the aromatic content of gasoline (*5*). The study reported here was made to determine how atmospheric visibility and soiling might be affected if motorists with pre-1971 cars were forced, by restrictions in the lead content of gasoline, to use unleaded gasoline of necessarily high aromatic content. Under realistic driving conditions, the exhaust aerosol generated by the use of unleaded fuel of predominately high aromatic content caused appreciably greater light absorption and soiling than that from low-aromatic leaded fuel.

An idle, concrete-surfaced traffic tunnel with a straight and approximately level two-lane roadway 2 km long was converted into a controlled environmental test chamber in which cars were driven according to the 7-mode federal test cycle (*6*). The large available working volume (7×10^4 m^3) allowed the attainment of exhaust dilution levels typical of those that occur in urban atmospheres without the uncertainties of proportional sampling. Because of the remote location of the tunnel in the Appalachian Mountains of southern Pennsylvania, freedom from sources of industrial or vehicular pollution provided clean ambient air for flushing the tunnel between tests.

Two four-car fleets (one 1969 model, two 1970 models, and one 1971 model) of matched standard automobiles were used, one fleet burning leaded gasoline and the other fleet burning unleaded gasoline. Companion pairs of cars of the same year, one burning leaded and the other burning unleaded gasoline, had similar histories of operation and mileage on their respective fuel types.

The cars of the leaded fleet were operated on premium fuels of low (25 to 26 percent) aromatic content representative of current commercially available gasoline. The pre-1971 cars of the unleaded fleet were fueled with a commercial premium unleaded gasoline of high (54 percent) aromatic content to satisfy their octane requirements, whereas the 1971 car of the unleaded fleet was satisfactorily operated on an unleaded gasoline with a low (27 percent) aromatic content. Companion cars in the two fleets were adjusted to factory specifications, and gaseous emissions were measured prior to testing. Periodic field checks of tail pipe