6. I. J. Eberstein, B. N. Khare, J. B. Pollack, *Icarus* **11**, 159 (1969).
7. A. T. Young, *ibid.* **18**, 564 (1973); G. T. Sill, *Commun. Lunar Planet. Lab.* **9**, 191 (1972); J. B. Pollack *et al.*, *Icarus* **23**, 8 (1974).
8. J. B. Pollack, D. W. Strecker, F. C. Witteborn, E. F. Erickson, B. J. Baldwin, *ibid.* **34**, 28 (1978).
9. E. S. Barker, *ibid.* **25**, 268 (1975); W. A. Traub and N. P. Carleton, in *Exploration of the Planetary System*, A. Woszczyk and C. Iwaniszewska, Eds. (Reidel, Dordrecht, Netherlands (1974), p. 223; E. S. Barker, *Bull. Am. Astron. Soc.*, in press.
10. R. G. Prinn, *Science* **182**, 1132 (1973).
11. J. S. Lewis, *Earth Planet. Sci. Lett.* **10**, 73 (1970).
12. L. D. G. Young, *Icarus* **17**, 632 (1972).
13. R. M. Goody, *Atmospheric Radiation*, I. *Theoretical Basis* (Oxford Univ. Press, London, 1964), p. 10; T. Owen, in *The Mars Reference Atmosphere* (COSPAR, Paris, 1979), p. 99.
14. T. Owen, *Icarus* **28**, 171 (1976); M. B. McElroy, Y. L. Yung, A. O. Nier, *Science* **194**, 70 (1976).
15. J. S. Lewis, *Earth Planet. Sci. Lett.* **22**, 239 (1974).
16. E. Anders and T. Owen, *Science* **198**, 453 (1977).
17. G. W. Wetherill, *Proc. 6th Lunar Sci. Conf.* (1975), p. 1539.
18. A. G. W. Cameron, *Space Sci. Rev.* **15**, 121 (1970).
19. D. C. Black, personal communication.
20. M. G. Natrella, *Experimental Statistics* (Handbook 91, National Bureau of Standards, Washington, D. C., 1966), pp. 5-27 to 5-46.
21. J. H. Hoffman, R. R. Hodges, Jr., M. B. McElroy, T. M. Donahue, M. Koplin, *Science* **203**, 802 (1979).
22. We acknowledge the superb engineering contributions of all of the TRW staff at Redondo Beach, Calif., and especially S. L. Korn, J. Vogrin, S. R. Rocklin, G. T. Rosiak, W. D. Potter, L. D. Balls, P. Staudhammer, and H. Suer. We acknowledge the NASA Ames Research Center support of W. Berry early in the program and W. Hightower later as well as C. Leidich, J. Terhune, M. Lehwalt, P. Kirk, and B. Berdahl throughout. We are especially indebted to C. Reichwein for the software.

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Wind Velocities on Venus: Vector Determination by Radio Interferometry

Abstract. *To determine the wind directions and speeds on Venus, as each Pioneer probe fell to the surface we tracked its motion in three dimensions using a combination of Doppler and long-baseline radio interferometric methods. Preliminary results from this tracking, coupled with results from test observations of other spacecraft, enable us to estimate the uncertainties of our eventual determinations of the velocity vectors of the probes with respect to Venus. For altitudes below about 65 kilometers and with time-averaging over 100-second intervals, all three components of the velocity should have errors of the order of 0.3 meter per second or less.*

Attempts to understand the temperature and velocity distributions of Venus's atmosphere through quantitative modeling have been severely limited by the lack of three-dimensional observational constraints, especially for the altitudes below the cloud tops (*1*, *2*). In order to obtain, for the first time (*3*), profiles of the vector wind velocities as functions of altitude in the atmosphere of Venus, we undertook the Pioneer Venus differential long-baseline interferometry (DLBI) experiment using the bus and the four-probe spacecraft (*4*).

In this experiment we did not measure wind velocities directly; rather, we monitored the velocity of each probe as it fell through the atmosphere. The two horizontal components of a probe's velocity, if averaged over intervals longer than a few seconds, are substantially equal to those of the ambient wind after the probe has descended to an altitude of about 65 km. Above this altitude, interpretation of the horizontal velocity measurements requires aerodynamic modeling, as does interpretation of the vertical component of the velocity at all altitudes.

For the determinations of all three velocity components, we relied upon Earth-based observations of the S-band (λ = 13 cm) radio signal that each spacecraft emitted. We combined Doppler-shift observations, which were sensitive to the projection of the velocity along the "line of sight" from the spacecraft to Earth, with long-baseline interferometric observations, which were sensitive to changes in the direction of this line. In the latter observations, an important advantage was gained by differencing the interferometric phases observed simultaneously for the bus and for each probe. The observable DLBI thus obtained is sensitive to the motion of the probe relative to the bus, but is relatively free from errors associated with the instrumentation and with the propagation medium (*4*). By the use of this differencing technique in conjunction with north-south and east-west interferometer baselines ~ 8000 km long, we are able to determine the transverse components of the probes' velocities with uncertainties quite comparable to those for the line-of-sight components.

The Pioneer Venus bus continued to follow a ballistic trajectory outside the atmosphere until after the impacts of all four probes, and its motion relative to the planet is determinable with velocity uncertainties of less than 10 cm sec^{-1} in all three components by means of conventional Doppler tracking and orbit-determination techniques (*5*). The combination of the Doppler and DLBI tracking of the bus and the probes thus can yield a determination of each probe's velocity vector with respect to Venus.

We believe that the uncertainties of our determinations, by Doppler tracking, of the line-of-sight velocities of the three small probes are each about 10 cm sec^{-1}, caused by uncertainties in the transmitted frequencies. These frequencies were controlled by onboard crystal oscillators (*6*). The large probe and the bus carried coherent transponders which enabled "two-way" Doppler observations to be made with equivalent velocity uncertainties of less than 1 cm sec^{-1}.

Redundant long-baseline interferometers were constructed for this experiment from the two antennas of 64-m diameter of the Deep Space Network (DSN) at Goldstone, California, and Canberra, Australia; and the 9-m antennas of the Spaceflight Tracking and Data Network (STDN) at Santiago, Chile, and Guam (*7*). The directional beam of each of these antennas, and the 2291- to 2293-MHz radio-frequency (RF) passband of a single receiver connected to each, included the signals from all five spacecraft simultaneously. To monitor the group and the phase delays, as well as the gains, of the receivers and all subsequent portions of our interferometry system, we also included in the RF input of each receiver a set of continuous low-level calibration signals whose frequencies spanned the passband; the signals were derived from an atomic hydrogen maser or a cesium-beam frequency standard at each site.

The entire RF band of signals 2 MHz wide was converted to the 0- to 2-MHz "video" band, then sampled at 0.24-μsec intervals, digitized with 3 bits per sample, time-tagged according to the local atomic clock, and recorded digitally on redundant magnetic tapes at each site. When the observations had been completed, the recordings were carried to the Jet Propulsion Laboratory (JPL).

There, they are filtered digitally to reduce the 2-MHz bandwidth to a set of seven spectral windows each about 1 kHz wide. Each window contains, in addition to noise, one continuous-wave signal: the carrier wave from one of the five spacecraft, or one of two band-edge calibration signals. These reduced-bandwidth data, also in digital form, are shipped to the Massachusetts Institute of Technology where the phase of each signal is estimated as a function of the time indicated by the receiving site's clock when the signal was originally recorded (*8*). Data processing, both for bandwidth reduction and for phase estimation, is proceeding as anticipated but is in-

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complete (*9*). However, several important results are already in hand:

1) Processing of the calibration-signal data is complete and shows that for the duration of the observations at all four tracking stations, the receiving and recording systems functioned perfectly, and that the contributions of any instabilities in these systems to errors in the probe velocity determinations should be insignificant (smaller than about 1 mm sec^{-1}).

2) Partial processing of bus and probe data from all four stations reveals signals of the expected strengths and phase stabilities. The probe data already examined include some from lower-atmosphere and postimpact observations; no difficulty from scintillation has been encountered.

3) Completed analyses of "control" experiments, in which we used all of the same equipment and computer programs for observations of other spacecraft that simulated the Pioneer Venus bus and probes with respect to their spatial or RF separations, or both (*10*), showed that errors from all relevant sources, including both "instrumental" effects and differential propagation medium effects, were equivalent to less than a velocity error of 10 cm sec^{-1} at Venus.

On the basis of these results and those of other detailed theoretical and experimental studies of error sources (*11*), we believe that the uncertainties of our final determinations of the velocity vectors of the Pioneer Venus probes, relative to Venus and averaged over intervals of 100 seconds, will be less than 0.3 m sec^{-1} for all components (*12*). In future reports, we hope to present such determinations and also to compare and combine them with the pressure, temperature, radiation-flux, vertical acceleration, turbulence, and composition measurements obtained from the other Pioneer Venus experiments, in order to better understand Venus's global atmospheric circulation.

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References and Notes

1. Such constraints are vital because of the strong coupling between the velocity and temperature fields, and the nonlinearity and three-dimensionality of the equations of motion.
2. For a discussion, see G. Schubert *et al.*, *Space Sci. Rev.* **20**, 357 (1977).
3. From Doppler observations of the Russian Venera 7, 8, 9, and 10 spacecraft, altitude profiles of wind speeds for Venus were inferred (*2*), but since such an observation is sensitive only to the (one-dimensional) projection of the spacecraft velocity along the line of sight, its interpretation is ambiguous. In particular, the direction of the wind cannot be determined, and the vertical descent rate of the spacecraft is not distinguished from any horizontal motion.
4. C. C. Counselman III, H. F. Hinteregger, I. I. Shapiro, *Science* **178**, 607 (1972): C. C. Counselman III, H. F. Hinteregger, R. W. King, I. I. Shapiro, *Science* **181**, 772 (1973); C. C. Counselman III, *Annu. Rev. Astron. Astrophys.* **14**, 197 (1976); L. Colin and D. M. Hunten, *Space Sci. Rev.* **20**, 451 (1977).
5. The day probe continued to transmit from the time that it reached the surface of Venus until the bus entered the atmosphere. The DLBI observations made during this interval yield a redundant determination of the bus orbit. The night probe, which transmitted a strong signal for 1 second after its impact, provides a useful check.
6. Results of extensive environmental tests performed before launch indicate that the random frequency variations throughout the period of our observations, from ~ 22 minutes before atmospheric entry until impact, should have been of the order of three parts in 10^{10}. The frequency stability over longer time intervals is unimportant because we can estimate each probe's transmitter frequency accurately, simultaneously with the parameters of its ballistic approach trajectory, by analysis of our preentry tracking data. This analysis, which we have not yet completed, will also yield a useful, independent assessment of each transmitter's short-term stability (*5*).
7. The DSN and the STDN are managed for the National Aeronautics and Space Administration (NASA) by the JPL and by the Goddard Space Flight Center (GSFC), respectively.
8. We take the difference between the phases, estimated separately for the signals received at two stations from a given spacecraft, to obtain an interferometric observable.
9. To appreciate the magnitudes of these tasks, consider two statistics: for this experiment, 10^{12} bits of data were recorded; and even the reduced-bandwidth data consist of 4×10^9 bits.
10. In particular, we determined the "unknown" relative horizontal velocities of pairs of Apollo lunar surface experiments packages. In another experiment, we observed the "separate" sources of two S-band signals, differing in frequency by 0.72 MHz, that were both emitted by the Voyager 1 spacecraft.
11. Pioneer Venus Project, *Differenced Long-Baseline Interferometry Experiment Design Review Document* (NASA Ames Research Center, Moffett Field, Calif., July 1977).
12. Time resolution of 100 seconds corresponds to altitude resolution of the order of 10 percent for altitudes about 10 km, and to ~ 1-km resolution at altitudes below 10 km, for both the large and the small probes. For averaging time intervals of less than 100 seconds but more than about 5 seconds, the uncertainty is set by the signal-to-noise ratios of the DLBI observations and is proportional to $t^{-1.5}$, where t is the averaging time.
13. We thank the crews of the Canberra, Goldstone, Guam, and Santiago tracking stations for their flawless execution of these intricate observations; D. W. Johnston (JPL) for DSN (*7*) training and operations support; G. Kronmiller, J. McKenzie, and P. Mitchell (all of GSFC) for STDN (*7*) engineering, training, and operations support; H. Donnelly and associates (JPL) for implementation of the calibration and receiver systems; K. Kimball and associates for the 12 Mbit sec^{-1} recorders; R. Tappan (JPL) for the bandwidth-reduction assembly; R. Speer and associates (Bendix) for bandwidth-reduction operations; A. E. E. Rogers and H. F. Hinteregger (both of Haystack Observatory) for contributions to the designs of the receivers and calibrators, and the tape recorders, respectively; J. Dyer (NASA Ames), W. Kirhofer (JPL), their associates, and P. Biraben (MIT) for important error analyses; and C. Hall (Pioneer Venus project manager), L. Colin (project scientist), and the project staff for support in innumerable ways. This report describes one phase of research carried out at the JPL, California Institute of Technology, under NASA contract NAS 7-100. The experimenters at the Massachusetts Institute of Technology were supported in part by contract NAS2-9476 with the NASA Ames Research Center.

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Pioneer Venus Radar Mapper Experiment

Abstract. *Altimetry and radar scattering data for Venus, obtained from 10 of the first 13 orbits of the Pioneer Venus orbiter, have disclosed what appears to be a rift valley having vertical relief of up to 7 kilometers, as well as a neighboring, gently rolling plain. Planetary oblateness appears unlikely to exceed 1/2500 and may be substantially smaller.*

The radar mapper experiment (*1*) carried aboard the Pioneer Venus orbiter spacecraft has three major scientific objectives. The first, and most important, is to measure the height of the spacecraft above the local surface immediately below. The second is to analyze the strength and delay distribution of the echo to determine the physical characteristics of the scattering region. These first two tasks are carried out simultaneously during that small portion (about 0.8 second in duration) of each spacecraft roll when the 30° beamwidth of the radar antenna, which is programmed to move appropriately in the plane containing the spacecraft's axis of rotation, sweeps across the nadir direction. The third objective is realized about 1.5 seconds earlier or later than the altimetry observations, when the antenna is directed by the spacecraft's rotation to one side or the other of the nadir. At these times, echoes are analyzed in delay and Doppler frequency, to obtain 64 picture elements of a relatively coarse side-looking radar scattering image. Because of echo-strength limitations, the imaging can only be carried out at altitudes less than approximately 500 km above the surface. Altimetry is possible at all spacecraft altitudes below 4700 km.

In the orbit achieved by the Pioneer Venus orbiter, altimetry is possible over a band extending from 74°N latitude through the equator to about 63°S. [We have used the following values for the Venus north pole position (1950:0);