and low-shear "layers" 1 to 3 km in vertical thickness, throughout the range 35 to 55 km altitude. These meridional shear layers may be related to alternations in the divergence of the net radiative flux observed on the day probe (*11*) below the clouds, and to the variations in particle density within the clouds (*12*). High shear seems to be associated with local radiative heating and with high cloud density. Particularly large values of uv are seen in the regions from 43 to 47 km and above 50 km. In the middle cloud at 55 km, $uv \approx -5000$ m^2/sec^2 and the sense is such as to provide an equatorward flux of easterly momentum. Convergence of this flux toward lower latitudes could provide easterly acceleration in equatorial regions. The very large values observed for both $\partial u/\partial z$ and $\partial v/\partial z$ in these upper regions also suggest the possibility of very large vertical advection of horizontal momentum. Since temperatures measured by the probes at the 1-bar level (*10*) appear to increase by up to 9 K from the equator to 30°S, then at 55 km $v(\partial T/\partial y) \approx -6$ K day^{-1}; a very significant local heating by equatorward advection by the meridional wind is indicated. Leovy (*13*) has also suggested that on Venus a cyclostrophic balance is present between the zonal winds and the meridional pressure gradient. A preliminary comparison of our wind measurements with the measured pressure differences between the north and day probes (*10*) appears, to first order, to confirm this hypothesis. We will examine the hypothesis more critically as soon as we have reduced the DLBI data for all four probes.

C. C. COUNSELMAN III
S. A. GOUREVITCH
R. W. KING
G. B. LORIOT
Department of Earth and Planetary Sciences, Massachusetts Institute of Technology, Cambridge 02139
R. G. PRINN
Department of Meteorology, Massachusetts Institute of Technology

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3. The continuation of radio transmission by the day probe while it was on the surface of Venus provided another useful check. We confirmed that during this time the estimated horizontal velocity components were zero, within the noise. We assumed that after impact the vertical velocity was zero, so that we could determine the probe's transmitter frequency as a function of time, simultaneously with the two horizontal velocity components. The frequency was observed to drift linearly at a rate of about 1 part in 10^{12} sec^{-1} for the first half-hour after impact. (A frequency change of 3000 parts in 10^{12} corresponds to a line-of-sight velocity change of ~ 1 m sec^{-1}.) The probe transmitter frequency and its rate of drift can also be estimated accurately through analysis of the interferometric and Doppler tracking data from the pre-entry (ballistic) portion of the probe's flight. This analysis has not been completed.
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15 May 1979

Measurements of Turbulence in the Venus Atmosphere Deduced from Pioneer Venus Multiprobe Radio Scintillations

Abstract. *The 2.3-gigahertz log-amplitude fluctuations observed in the radio links of the Pioneer Venus entry probes during Venus encounter have been used to study turbulence in the Venus atmosphere. The deduced estimates of the upper bound of structure constant* c_n *of the refractive index fluctuations* ($c_n \lesssim 4 \times 10^{-8}$ cm$^{-1/3}$) *are inconsistent with similar entry probe measurements by Veneras 4 to 8 but are consistent with the radio occultation measurements by flyby (Mariners 5 and 10) and orbiting (Venera 9) spacecraft. The Pioneer Venus measurements therefore provide a resolution of the long-standing order of magnitude discrepancy between these earlier measurements of* c_n.

The radio links of the Pioneer Venus orbiter and probes offer an excellent opportunity for conducting complementary measurements of turbulence in the Venus atmosphere based on an analysis of the observed radio scintillations. So far only the multiprobe data have been processed, and these results are discussed in this report.

The Pioneer Venus multiprobe measurements are especially interesting because they should help resolve the order of magnitude difference between estimates of the structure constant c_n of the refractive index fluctuations (*1*) deduced from the earlier entry probes Veneras 4 to 8 (*2*) and those inferred from the radio occultation measurements by Mariners 5 and 10 (*3*) and Venera 9 (*4*). This important discrepancy and its implications in terms of the dynamics of the Venus atmosphere have been the subject of much discussion (*5*).

The mission features of the Pioneer Venus multiprobe Venus encounter on 4 December 1978 have been described by Colin (*6*). The communication angles (the angle the line of sight makes with the local Venus zenith) for the four probes ranges from 53° to 61°. Figure 1 shows the power level time histories of the 2291- to 2293-MHz radio-frequency (RF) signals received from the probes at the 64-m Deep Space Network (DSN) station in Canberra, Australia, during the Venus encounter. These narrowband data, recorded at a sampling rate of one per second, were intended for station monitoring purposes only, but are displayed here to show major events and features. The corresponding altitude of the probes as a function of time has been discussed previously (*7*). It is clear from Fig. 1 that while the intensity of the amplitude fluctuations increases for the small probes after RF blackout, it does not in the case of the large probe. Furthermore, the high-frequency fluctuations in the day probe signal are reduced considerably after landing on Venus, but a slowly varying component with a period of the order of minutes persists.

To analyze the observed amplitude fluctuations, we used the higher-quality wideband (approximately 1 kHz) recordings made at the 64-m DSN stations in Goldstone, California, and Canberra, Australia. These recordings also represent the source of data for the Pioneer Venus differential long-baseline interferometry (DLBI) experiment and have already been described (*8*). The RF spectra for the day probe shortly before and after impact on Venus are shown in Fig. 2. We further reduced the bandwidth of the 1-kHz data to 2 Hz by using a digital phase lock loop procedure. Fluctuation power spectra of log amplitude were produced by using a fast Fourier transform (FFT) algorithm; the results for the large and day probes for time intervals A through E defined in Fig. 1 are shown in Fig. 3.

The downturn at about 1 Hz in every

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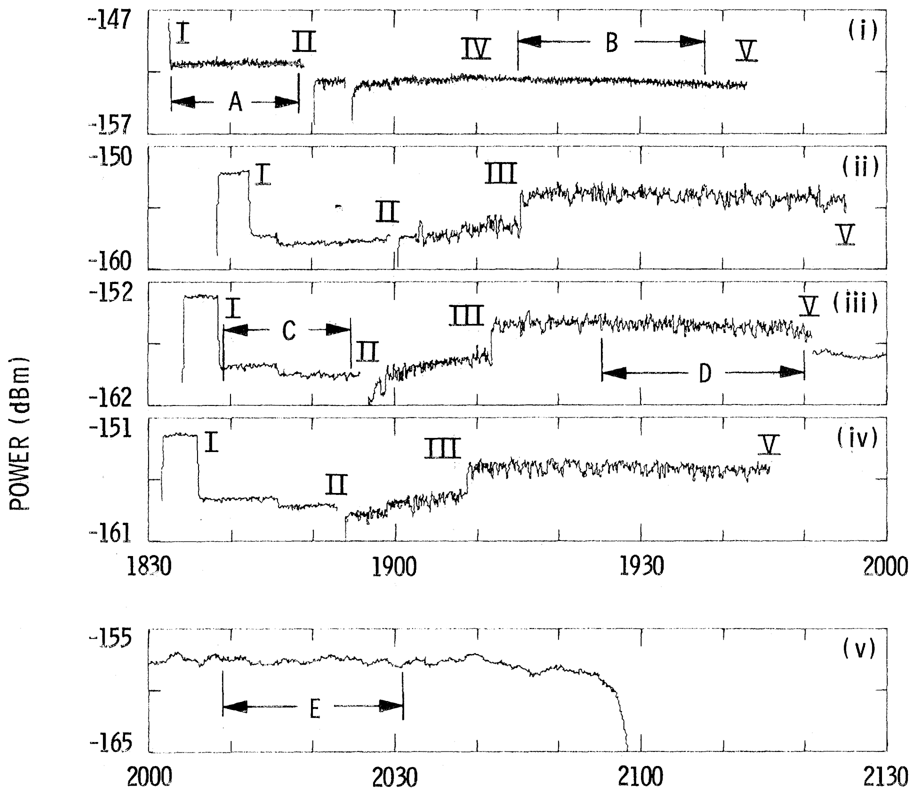

Fig. 1. Time series of amplitude for the Pioneer Venus probes: (i) large probe (sounder), (ii) north probe, (iii) day probe, (iv) night probe, and (v) day probe after impact. Abscissa is ground-received time in universal time (UT) at the Australian station. The time events are as follows: (*I*) telemetry turn-on, (*II*) RF blackout, (*III*) bit-rate change, (*IV*) parachute jettison, and (*V*) impact.

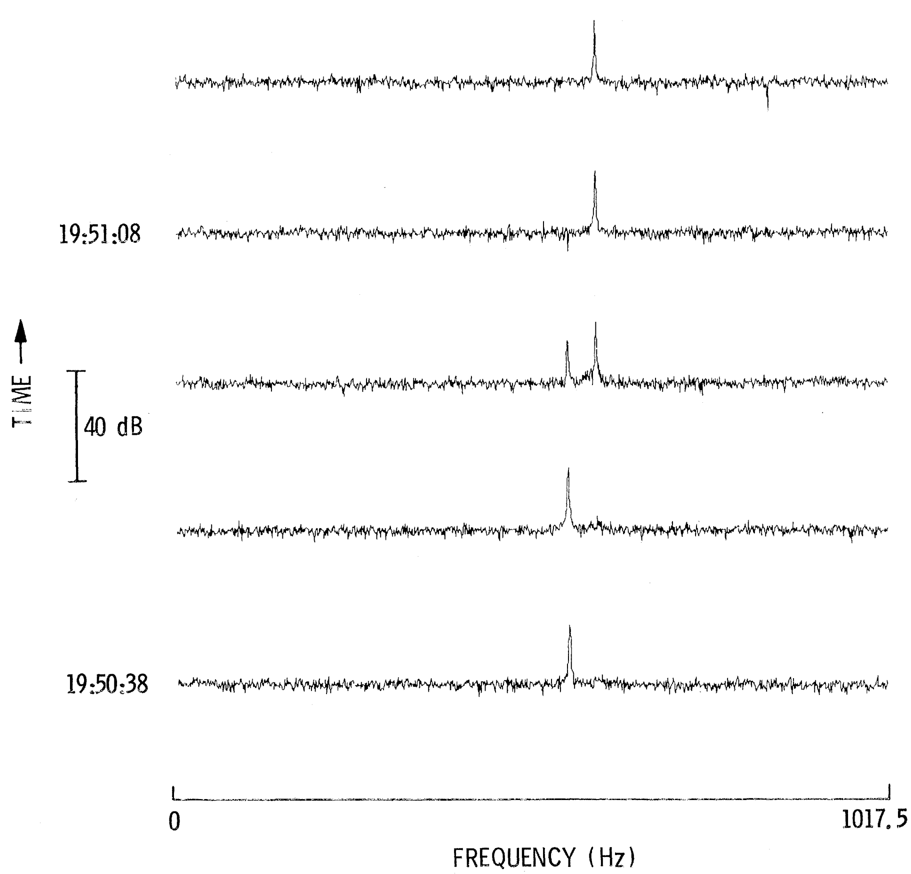

Fig. 2. Radio-frequency spectra as functions of time for the day probe near impact. Time increases toward the top. Each spectrum is computed from 10 seconds of data. In the central spectrum, the integration period includes Doppler rates before and after impact.

Table 1. Estimates of the upper bound of the structure constant.

Horizontal wind speed (m/sec)	Homogeneous turbulence c_n (cm$^{-1/3}$)	Turbulence layer c_{n0} (cm$^{-1/3}$)
100	2.6×10^{-8}	4.2×10^{-8}
50	1.9×10^{-8}	3.0×10^{-8}
10	8.4×10^{-9}	1.33×10^{-8}

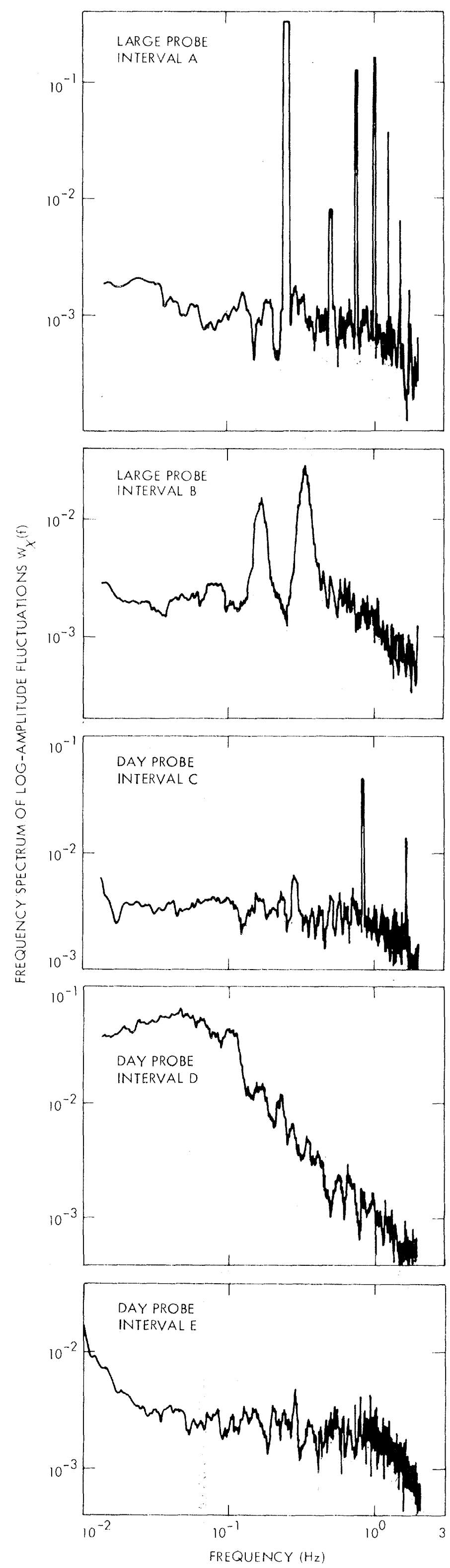

Fig. 3. Fluctuation power spectra of log amplitude for intervals indicated in Fig. 1 (see text).

spectrum reflects the filter used in the bandwidth-reducing process. Before RF blackout, the spectra (for instance, intervals A and C in Figs. 1 and 3) are basically white with spectral density levels near those expected from receiver noise for signal-to-noise ratios (SNR) in the range 27 to 30 dB in a 1-Hz bandwidth. The discrete peaks in each spectrum occur at frequencies corresponding to the fundamental probe spin rate and its harmonics and arise because of the azimuthal ripple in the probe antenna patterns. The spectrum for the large probe while descending through the Venus atmosphere (interval B) remains essentially unchanged, except for an increase in spectral density level due to a decrease in SNR and a shift and broadening of the discrete peaks due to a changing probe spin rate. On the other hand, the spectrum for the day probe (interval D) shows continuous structure, which is typical of all the small probes during their descent in the atmosphere. After the day probe lands on Venus its spectrum (interval E) reverts to that of receiver noise for fluctuation frequencies higher than about 0.02 Hz. It is clear that the fluctuations in signal strength of the small probes during their descent through the atmosphere were caused by probe motion combined with the nonuniform probe antenna power pattern. In contrast, the large probe was more stable so that the signal fluctuations observed were essentially those of receiver noise and spin rate modulation.

The characteristic fluctuation frequency of the turbulence-induced amplitude scintillations is given by the Fresnel frequency (*1*). If we assume that turbulence exists over an altitude range of 60 km and that the horizontal wind velocity varies from 10 to 100 m/sec, then for a probe near the surface of Venus having a communication angle of 60°, the corresponding Fresnel frequency ranges from 0.04 to 0.4 Hz. The measured spectra of the large probe in the lower atmosphere and of the day probe on the surface of Venus in this range are those of receiver noise. Thus, scintillations due to atmospheric turbulence were not detected by the Pioneer Venus probes. Estimates of the upper bound on the structure constant c_n can be obtained by equating the measured noise level to the theoretical log-amplitude scintillation spectrum for fluctuation frequencies less than the Fresnel frequency. Two models of atmospheric turbulence were used: one in which the turbulence is homogeneous with constant c_n over an altitude range of 60 km, and one in which the turbulence is located in a region in the upper atmosphere with c_n described by $c_{n0}^2 \exp [(z - L)/a]^2$ (where z is altitude and $L = 60$ km is the altitude and $a = 6$ km is the extent of the region of strong turbulence). The latter model is based on the radio occultation measurements of Venus (*3, 4*); the turbulence in the upper atmosphere may be caused by the region of instability observed by the Pioneer Venus probes in the middle cloud at 52 to 56 km (*9*). Estimates of the upper bound on c_n and c_{n0} from these two models are summarized in Table 1. Based on the results of Venera 4 to 8 ($c_n \sim 10^{-7}$ cm$^{-1/3}$), it is surprising that scintillations were not detected by Pioneer Venus. On the other hand, the estimates of the upper bound on c_n deduced from the Pioneer Venus measurements are consistent with the radio occultation results ($c_{n0} \sim 10^{-8}$ cm$^{-1/3}$). The Pioneer Venus results therefore indicate that the fluctuations seen by Venera 4 to 8 were probably not caused by atmospheric turbulence and explain the long-standing discrepancy between these earlier measurements of c_n.

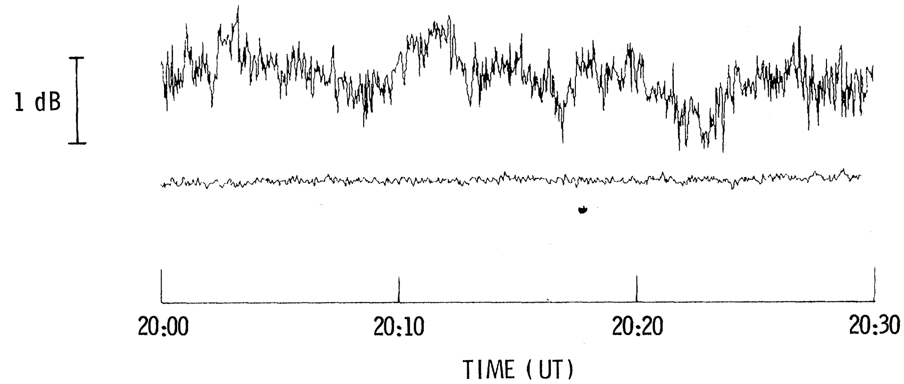

Fig. 4. Time series of amplitude based on wideband recordings at the California station. (Upper curve) Day probe after impact; (lower curve) calibration signal injected in receiving system at the same time. The time series were processed identically with a time constant of about 1 second. High-frequency noise on the calibration signal is smaller because the signal-to-noise ratio is larger than that of the day probe by about 12 dB.

The slowly varying fluctuations (frequency $\lesssim 0.02$ Hz) observed in the signal level after the day probe landed on Venus are not due to the receiving equipment because it occurred at both 64-m stations [see Fig. 4 for a comparison of the day probe signal with one of the calibration tones described in (*8*)]. These fluctuations may be of terrestrial origin since they are not significantly correlated between the 64-m stations.

The results of this study imply that receiver noise rather than phase scintillations is the dominant noise source for the DLBI experiment. For frequencies higher than the Fresnel frequency the phase and log-amplitude scintillations have identical spectra for weak fluctuations (*1*), and we found that the amplitude scintillations are lower than the receiver noise level. For frequencies higher than the Fresnel frequency the DLBI technique of differencing the phase at two receiving stations on Earth removes the phase scintillations to first order.

RICHARD WOO, J. W. ARMSTRONG
Jet Propulsion Laboratory, California Institute of Technology, Pasadena 91103
WILLIAM B. KENDALL
Mark Resources, Marina del Rey, California 90291

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