Earth-Based Radio Tracking of Galileo Probe for Jupiter Wind Estimation

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The Galileo probe transmitted a signal to the orbiter during its descent through the Jupiter atmosphere on December 7, 1995. Although the probe was not designed to communicate to the 1 ;arth, wc detected the probe radio signal at two liarlh-based radio observatories, where the signal was a billion times weaker than at the orbiter. Jupiter zonal wind speed can be deduced from the Doppler shift of the probe signal. Since the probe-]iarth was nearly parallel to the zonal winds, while the probe-orbiter path was nearly perpendicular, the P.arih-based wind estimates should be less sensitive to atmospheric modeling errors. Our wind profile based on the probe-Ear[h data qualitatively agrees with the profile based on the probe-orbiter data; both show high wind speeds at all depths sampled, indicating that the winds are driven by internal convection rather than solar heating.

On December 7, 1995 the Galileo probe entered the atmosphere of Jupiter. Onc of the goals of the probe mission was to determine the Jovian zonal (cast-west) wind speed as a function of altitude by measurements of the Doppler shift of the probe radio signal received by the orbiter. Prior to the Galileo mission, various combinations of Doppler, radio interferometric, and in situ measurements of atmospheric probes from the Pioneer, Venera, and Vega missions have been used to investigate the wind speed on Venus (1). As a Galileo mission design compromise, the orbiter was nearly above the probe throughout the descent to maximize the signal received by the orbiter, and thus the probe-orbiter link was nearly perpendicular to the zonal wind direction. This creates some ambiguity in interpreting the probe-orbiter Doppler shift, since vertical updrafts and down drafts or meridional winds could cause Doppler shifts potentially as large as the zonal winds.

After the Galileo mission was launched, it was realized that the probe radio signal could be directly detected at the Earth for at least part of its descent even though the signal power was 10^9 times weaker at the Earth than at the orbiter. The advantage of observing the probe radio signal from the Earth was that, because the probe-liatth direction was almost aligned with the zonal wind direct ion, the probe Doppler shift as received at the Earth was much more sensit ive to the zonal wind speed than to vertical or meridional motions.

The Galileo probe transmitted data to the orbiter on two channels near 1387 MHz (21.6 cm). Probe telemetry was sent at 256 symbols/s on each channel during the entire descent of the probe through the atmosphere with a fully-suppressed carrier. One of the two probe channels was controlled by an ultra-stable oscillator (USO). This oscillator provided the frequency stability over the descent of the probe necessary to ensure that oscillator drifts were not interpreted as changes in the Doppler shift of the received signals, and hence, changes in the wind speed. The probe carrier frequency received at the orbiter was compared to the frequency of a similar USO on the orbiter. The differenced frequency data were transmitted to the Earth. Through the Doppler effect, these differenced frequency values provide a measure of relative velocity between the probe and the orbiter along the probe-orbiter direction. This velocity measurement did not provide absolute velocity of the probe in this direction, but rather the sum of probe velocity and a (nearly) constant unknown bias, with the bias caused by the difference of the unknown frequency offsets of the probe and orbiter oscillators from their nominal frequencies. This offset was expected to remain effectively constant, after known warm-up transients arc removed, throughout the active lifetime of the probe. The uncalibrated portion of the frequency drift during the descent should not limit the accuracy of the velocity measurements.

The probe antenna pointed vertically, with the orbiter nearly overhead for best reception of the probe telemetry. The Earth was near the horizon as seen from the probe. Consequently the antenna gain in the Earth direction was low, The power transmitted in the direction of the Earth was about 60 times less than the vertical power near the beginning of the probe transmission. As the probe descended the rotation of Jupiter caused the probe antenna to point farther from the Earth so that the power transmitted towards the Earth decreased to 200 times less than the vertical power 35 minutes after probe entry. In addition the Earth was about 4000 times farther from the probe than the orbiter was.

During the probe descent, the Very Large Array in Socorro, New Mexico was configured to point at the Galileo probe with the signals from all 27 antennas combined to provide a collecting area equivalent to that of a 130m diameter radio antenna. The. Australia Telescope Compact Array in Narrabri, Australia, was similarly configured as a back-up site, with its 6 antennas combined to form the equivalent of a 54m diameter antenna. Since the probe signal was 100'% phase-modulated by the telemetry stream, real-time detection of the probe signal required sufficient signal-to-noise (SNR) in one symbol-time (-4 ins), which could be achieved at the orbiter but not at the Earth sites. Instead the Earth sites performed a wide-bancl open-loop recording of the probe signal for later processing. By using the known probe symbol stream, as relayed by the orbiter to the Earth, the phase modulation on the probe signal due to the telemetry could be removed from the open-]oop recording of the probe signal, which allowed longer coherent integrat ion times. The probe signal was successful 1 y detected at both Earth sites.

After removal of the telemetry modulation, the SNR at the VLA would have been adequate to determine the probe radio frequency with a simple phase-locked-]oop algorithm if the signal frequency had been changing slowly enough. However the probe was apparently swinging throughout its descent causing continual changes in the radio frequency. This swinging of the probe was first detected in the probe transverse-accelerometer data (2), but was also seen in the probe-orbiter Doppler data (3) and in the amplitude of the probe signal received by the orbiter (4). The amplitude of the swinging caused the frequency of the probe signal as received at the VLA to change by ±5 Hz with a 5 second period. With this level of frequency change the VLA recording did not provide adequate SNR for carrier phase tracking. Instead, in order to get a preliminary wind profile we used a signal processing technique where power spectra of the recorded signal were formed for short (O. 1 s) intervals, and then averaged over 12 seconds. With this procedure the frequency variations caused by the pendulum motion were usually within a single (1 O 1 Hz) frequency bin, and averaging of independent power spectra was used to achieve adequate SNR for signal detection. This method was used to estimate the probe frequency for the first 17 minutes of probe transmission, during which the atmospheric pressure experienced by probe-Earth signal would have passed though several hundred kilometers of the cloud layer, making the probe signal undetectable. No strongly-absorbing clouds were found at the probe site by in situ measurements (8) and the probe signal was detected at Earth at least down to 7 Bar. At the 7 Bar level the probe-Earth signal would pass through the base of the postulated cloud layer about 1400 km from the probe site so the detection of the probe signal at the Earth indicates the absence of strongly absorbing clouds far from the probe site. This is consistent with ground-based infra-red observations of the probe site which show the entry site to be in a clear region of several thousand kilometers in extent (9). in the absence of water/anmlonia clouds, the dominant absorption of the k;ar[h-probe signs] is expected to be due to ammonia present in Jupiter's atmosphere. Assuming that Jupiter's atmosphere contains ammonia given by the solar abundance of nitrogen, the expected signal attenuation for Earth reception is about a factor of 1.6 when the probe was at a pressure of S Bar and about 2.5 when the probe was at 7 Bar. Wc expect to be able to measure the amplitude with an accuracy of 15% or better on short time scales and, with averaging, better on longer time scales. Thus further analysis of the probe-Earth data may provide a significant measurement of the amount of ammonia, and hence nitrogen, in Jupiter's atmosphere, This is of especial interest since there has been some difficulty with the probe's mass spectrometer measurements of this key constituent (10).

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7. Using a revised vertical descent profile, based on calibrated in situ probe temperature and temperature measurements, the Jupiter zonal wind speed profile based on only the probe-orbiter Doppler measurements has changed from (3) to agree better in character with Fig. 1 and indicates a lower average wind speed level by about 2.0 m/s. D. Atkinson, private communication (1 996)
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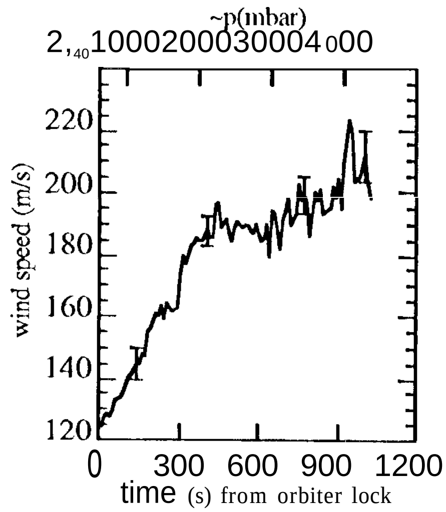

Figure 1. Estimated Jupiter zonal wind profile from Galileo probe mission from the signal as received by the VLA. The error bars indicate measurement and modeling errors affecting changes in the wind speed. A constant bias error of about 30 m/s may exi st, based on the preliminary probe descent profile; the uncertainty should be reduced to a few m/s or less when a final descent profile is available.