Galileo Doppler Measurements of the Deep Zonal Winds at Jupiter

David H. Atkinson, James B. Pollack,* Alvin Seiff

Changes in the speed of the Galileo probe caused by zonal winds created a small but measurable Doppler effect in the probe relay carrier frequency. Analysis of the probe relay link frequency allows direct measurements of the speed of Jupiter's zonal winds beneath the cloud tops. The deep winds were prograde and strong, reaching a sustained 190 to 200 meters per second at an altitude marked by a pressure of 24 bars. The depth and strength of the zonal winds severely constrain dynamic modeling of the deeper layers and begin to rule out many shallow weather theories.

Direct measurements of planetary winds during earlier missions provide an impressive legacy for the Galileo Doppler wind experiment. The Pioneer, Venera, and Vega missions to Venus used a combination of Earth-based Doppler tracking, radio interferometric techniques, and in situ measurements to deduce the two- and three-dimensional motion of the spacecraft as it descended from altitudes of 65 km to the surface (*1*). Measurements of winds on Mars were also successfully made at altitudes between 1.5 and 4.5 km by instrumentation on board the Viking landers, including Doppler radar, radar altimeter, and the accelerometers and gyroscopes of the inertial reference unit (*2*). With the success of the recent Galileo probe mission to Jupiter, it is now possible to extend this heritage of in situ wind measurements to the outer planets. Although similar to previous missions in concept, the Galileo Doppler wind measurements differ in application for three significant reasons: (i) the size and rapid rotation of Jupiter, (ii) the restriction of probe tracking to Doppler measurements along the line of sight by the Galileo orbiter (*3*), and (iii) the poor viewing geometry dictated by the orbital mechanics of the Galileo orbiter trajectory. The Galileo Doppler wind measurements begin to place constraints on the sources of energy contributing to the atmospheric dynamics at different levels. In addition, the in situ measurements of the winds by the probe will provide ground-truth verification for observations of Jupiter from the Galileo orbiter, as well as Earth-orbiting and ground-based observatories.

One of the two redundant data strings transmitted by the probe to the orbiter was driven by an ultrastable oscillator (USO). Although the probe USO was designed for maximum stability over intervals of several tens of minutes, the USO absolute frequency may have changed by as much as several hundred hertz during the 6-year cruise to Jupiter. The wind retrieval algorithm was developed to reduce the effects of uncertainties in the absolute frequency (*4*) by instead considering differences in measured Doppler frequencies. This approach also greatly diminished contributions to the Doppler profile that were slowly varying with time, including targeting errors in the longitude and latitude of probe entry and descent.

The inversion algorithm developed to retrieve the wind speed accounted for both the instantaneous and the time-integrated effects of the winds on the longitude of the probe's descent (*5*). Doppler residuals were obtained by subtracting the change in the nominal (modeled) link frequencies, $f_{\mathrm{nom}}(t) - f_{\mathrm{nom}}(t_0)$, from the change in the measured frequencies at time t, $f(t) - f(t_0)$, where t_0 is the time at which the orbiter receivers locked onto the probe signal. The nominal frequencies were calculated from the reconstructed probe and orbiter trajectories generated by the Galileo navigation team (*6*) and best estimates of the probe and orbiter USO frequencies and drift rates. On the basis of prelaunch and in-flight performance tests of the probe and orbiter USOs, we generated a profile of Doppler residuals that included adjustments for short-term drift (*7*, *8*). The exact Doppler shift equation was used with second- and higher-order Doppler terms and special and general relativistic (gravitational redshift) effects included. Measurements were obtained every 4/3 s throughout the 57.5 min of probe data, totaling 2590 frequency samples. The zonal winds were modeled by a polynomial in the logarithm of atmospheric pressure that gave a best fit to the frequency residuals in the least squares sense. The slope of the measured Doppler residuals was nearly constant and parallel to the reference case of 200 m s^{-1} (Fig. 1), suggesting that the zonal winds were also relatively constant and strong to the end of the probe mission.

To the depth at which contact with the probe was lost, marked by an atmospheric pressure of about 24 bars, the measured winds were prograde and strong, with speeds above 190 m s^{-1} (relative to System III) from 3 to 20 bars. Two noticeable fluctuations appear in the otherwise relatively constant profile: (i) a drop in the speed of the winds between about 0.4 and 3 bars and (ii) a sudden upturn in the winds near 20 bars. The winds measured in these regions could have alternate explanations. If the winds were constant at 200 m s^{-1}, the dip in wind speed in the upper atmosphere could be explained by the probe encountering a downflow of 4 m s^{-1} in this region. The apparent increase in winds deep in the atmosphere is likely related to excursions of the probe USO frequency caused by the extreme temperatures, reaching 388 K at 24 bars.

Although detailed error analyses have not been completed, Fig. 2 shows the retrieved winds with a constant ±5% error in probe descent speed, combined (root sum squared) with the 1σ (0.3°) and 3σ (0.82°) errors in probe descent longitude. The error bars for probe descent speed decrease as the

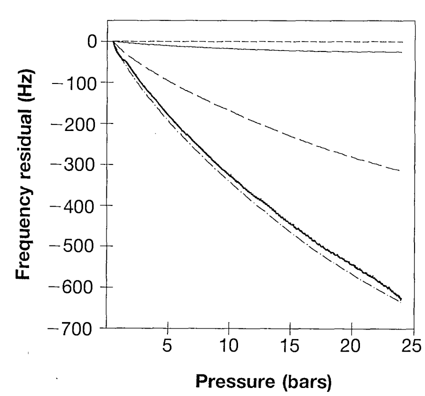

Fig. 1. Measured probe frequency residuals (light solid line) and frequency residuals from probe descent through a windless atmosphere with no errors (short dashes), a constant 100-m s^{-1} wind (long dashes), a constant 200-m s^{-1} wind (dot-dash), and a windless atmosphere with an error in probe descent longitude of 1.0° (heavy solid line).

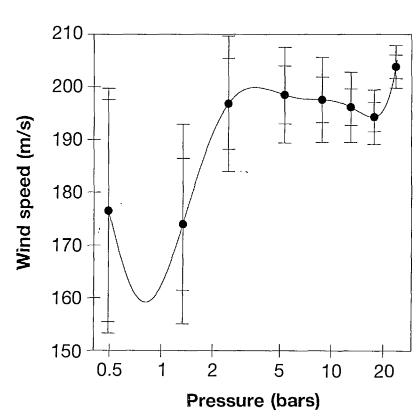

Fig. 2. Retrieved wind profile from 0.49 to 24 bars with error bars for 1σ (0.3°) and 3σ (0.82°) descent longitude offsets and 5% error in probe descent speed.

D. H. Atkinson, University of Idaho, Moscow, ID 83844, USA.
J. B. Pollack, NASA Ames Research Center, Moffett Field, CA 94035, USA.
A. Seiff, San Jose State University Foundation, NASA Ames Research Center, Moffett Field, CA 94035, USA.
*Deceased

probe moves away from the point of overflight where the geometry favors the vertical velocities. The error bars from probe longitude errors also decrease late in the descent because of the increasing importance of the integrated effect of the winds on the probe location relative to the diminishing effect of the initial longitude offset.

Since the late 19th century, optical measurements of Jupiter's winds have remained extremely repeatable. Optical tracking can, however, underestimate wind speeds in narrow zonal jets; this is especially true when the motions of larger and smaller clouds are compared (*9*). Although our measured winds are high compared to earlier results (*10*), Beebe *et al.* (*11*) point out that Voyager and Earth-based observations track the motion of large, organized cloud systems and are therefore not ideal tracers of the winds. The smallest clouds observed by Beebe *et al.* show an eastward jet at the latitude of the probe entry with a speed well within the measured Doppler wind error bars. In addition, under the assumption of hydrostatic equilibrium and geostrophic flow (balanced Coriolis and pressure forces), interpretation of Voyager infrared data shows that the winds in the stratosphere increase with decreasing altitude, at least to the cloud tops (about 0.4 bar). Interpretation of the results from Voyager beneath this altitude is difficult because of the complicating effects of aerosols (*12*).

The zonal winds remain strong to depths far greater than those at which solar energy is deposited (*13*), thereby providing support for the theory that the energy responsible for much of the atmospheric circulation originates in convective upwelling from the deep interior of Jupiter. The atmospheric motions associated with convective processes may provide the transport of momentum needed to power the zonal circulation. If this is indeed the case, then the deep interior of Jupiter is expected to configure itself into counterrotating cylinders concentric with the planetary spin axis (*14*). At the very least, the circulation at the cloud tops is indicative of deep atmospheric processes, and our results seem to rule out the theory of dynamic control of the winds attributable to solar absorption alone. Of course, we do not completely abandon the possibility of contributions to the dynamic processes from solar absorption, latent heat, layering of molecular weight associated with a water condensation altitude, and buoyancy differences attributable to horizontal gradients in the ortho/para ratio of hydrogen (*15*).

After the initial wind retrieval, the probe descent longitude was updated to include the effect of the winds, and the wind recovery was repeated. This process reduced the effect of second- and higher-order errors and rapidly converged to the resultant wind profile. After several iterations, the effect of the winds had been removed, and the frequency residuals showed a fine structure (Fig. 3), possibly related to the probe spin, swing beneath the parachute, or some other dynamical effect. The amplitude of the residuals tended to increase as the probe descended beyond the point of overflight (about 3.9 bars), exactly as expected for spin or a pendulum motion of the probe beneath the parachute. The peak to peak amplitudes of the oscillations were 2 to 3 Hz, corresponding to a variation in the line-of-sight velocity of about 0.5 m s^{-1}. Casual counting of peaks show about 8 to 10 peaks in each 200-s interval, corresponding to a period of 20 to 25 s. Upon closer examination, a higher frequency component is seen with a period of about 5 s (Fig. 4). This corresponds closely to Woo's measurements of signal amplitude variation (*16*), presumably the result of probe swing. Because the antenna was not aligned with the spin axis, the probe spin contributes to the residuals with a period that decreases during descent. The peak to peak amplitude of the spin component was expected to be about 0.2 Hz near overflight, increasing to 1.0 Hz at 24 bars. Other likely contributors to the measured residuals include atmospheric waves, turbulence, and aerodynamic buffeting.

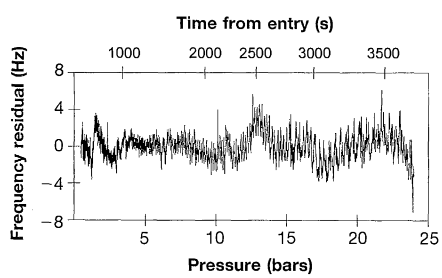

Fig. 3. Frequency residuals (after the effect of measured winds was removed) from about 230 to 3680 s after entry (0.49 to 24 bars).

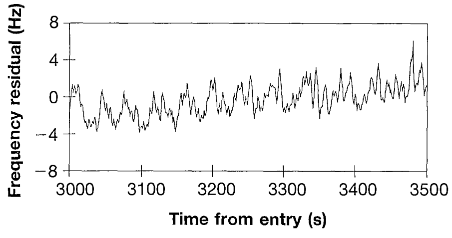

Fig. 4. Frequency residuals (after the effect of measured winds was removed) from 3000 to 3500 s after entry.

REFERENCES AND NOTES

1. V. V. Kerzhanovich, M. Ya. Marov, M. K. Rozhdestvensky, *Icarus* **17**, 659 (1972); V. V. Kerzhanovich and M. Marov, *ibid.* **30**, 320 (1977); C. C. Counselman *et al.*, *Science* **203**, 805 (1979); C. C. Counselman III *et al.*, *J. Geophys. Res.* **85**, 8026 (1980); R. A. Preston *et al.*, *Science* **231**, 1414 (1986); R. Preston *et al.*, *Adv. Space Res.* **7**, 299 (1987); D. Crisp, A. P. Ingersoll, C. E. Hildebrand, R. A. Preston, *ibid.* **10**, 109 (1990); R. Z. Sagdeyev *et al.*, *Astron. Astrophys.* **254**, 387 (1992).
2. A. Seiff, *J. Geophys. Res.* **98**, 7461 (1993).
3. B. Preston and W. Folkner have attempted to detect the probe signal from Earth using the Very Large Array (VLA). Because of the small effective isotropic radiated power of the probe, the extremely poor viewing geometry, and the large distance to Jupiter, the signal-to-noise ratio is very low; therefore, the results of the VLA observations are still pending. A positive result would provide a near line-of-sight projection of the zonal winds and offer a geometrically favorable means of measuring the winds in the upper atmosphere.
4. Errors in transmitted or measured frequencies are indistinguishable from the Doppler effects resulting from changes in the probe-orbiter line-of-sight velocity. At the nominal relay link frequency of 1387 MHz, a change in frequency of 4.6 Hz mimics the Doppler shift from a 1-m s^{-1} variation in the line-of-sight velocity. If the probe aspect angle is 5°, this shift cannot be distinguished from a zonal wind of 11.5 m s^{-1}.
5. D. Atkinson, thesis, Washington State University (1989); J. B. Pollack, D. H. Atkinson, A. Seiff, J. Anderson, *Space Sci. Rev.* **60**, 143 (1992).
6. The probe and orbiter trajectories are based on the Galileo navigation team OD105 (orbit determination number 105) and OD108 solutions, respectively. The OD105 probe entry and descent trajectory includes the 53-s delay in probe parachute deployment and is based on descent through the nominal, quiescent atmosphere. OD108 includes Doppler tracking of the orbiter from 21 November 1995 to 30 January 1996 for purposes of reconstructing the Io flyby.
7. Short-term drift rates are defined in terms of fractional frequency drifts over 30 min. On the basis of three in-flight performance tests, the probe USO drift rate was predicted to be 1.73×10^{-9} over 30 min, with an uncertainty of $\pm 0.93 \times 10^{-10}$, corresponding to an absolute drift in frequency of 2.4 Hz with an uncertainty of 0.13 Hz in 30 min.
8. S. B. Engstrom, thesis, University of Idaho (1995); Y. Wei, thesis, University of Idaho (1995); P. C. Garriga, *IDC Ref. HS373-2267* (Hughes Aircraft, El Segundo, CA, December 1982); V. Joshi, *IDC Ref. HS373-3732* (Hughes Aircraft, El Segundo, CA, July 1985); P. C. Garriga, *IDC Ref. HS373-1474* (Hughes Aircraft, El Segundo, CA, April 1980); J. Neff, *JPL D-1038, Rev. C* (Jet Propulsion Laboratory, Pasadena, CA, 1994); *Doc. HS 373-2293* (Hughes Aircraft, El Segundo, CA, 1981).
9. R. F. Beebe and A. P. Ingersoll, *J. Geophys. Res.* **86**, 8733 (1981).
10. G. Hunt, *Nature* **280**, 778 (1979); S. Limaye *et al.*, *Icarus* **65**, 335 (1986).
11. R. F. Beebe, A. A. Simon, L. F. Huber, *Science* **272**, 841 (1996).
12. P. J. Gierasch, B. J. Conrath, J. Magalhaes, *Icarus* **67**, 456 (1986).
13. D. M. Hunten, M. Tomasko, L. Wallace, *ibid.* **43**, 143 (1980).
14. F. H. Busse, *Icarus* **29**, 255 (1976); A. P. Ingersoll and D. Pollard, *ibid.* **52**, 62 (1982).
15. P. J. Gierasch, *ibid.* **29**, 445 (1976); *Science* **219**, 847 (1983).
16. R. Woo, personal communication.

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