LETTERS

The vertical profile of winds on Titan

M. K. Bird[1], M. Allison[2], S. W. Asmar[3], D. H. Atkinson[4], I. M. Avruch[5], R. Dutta-Roy[1], Y. Dzierma[1], P. Edenhofer[6], W. M. Folkner[3], L. I. Gurvits[5], D. V. Johnston[3], D. Plettemeier[7], S. V. Pogrebenko[5], R. A. Preston[3] & G. L. Tyler[8]

One of Titan's most intriguing attributes is its copious but featureless atmosphere. The Voyager 1 fly-by and occultation in 1980 provided the first radial survey of Titan's atmospheric pressure and temperature[1,2] and evidence for the presence of strong zonal winds[3]. It was realized that the motion of an atmospheric probe could be used to study the winds, which led to the inclusion of the Doppler Wind Experiment[4] on the Huygens probe[5]. Here we report a high resolution vertical profile of Titan's winds, with an estimated accuracy of better than 1 m s^{-1}. The zonal winds were prograde during most of the atmospheric descent, providing *in situ* confirmation of superrotation on Titan. A layer with surprisingly slow wind, where the velocity decreased to near zero, was detected at altitudes between 60 and 100 km. Generally weak winds (~1 m s^{-1}) were seen in the lowest 5 km of descent.

Titan's winds have been the subject of many investigations since that first close-up look from Voyager nearly 25 years ago. The infrared observations revealed a distinct pole-to-equator latitudinal contrast in temperature, varying from $\Delta T \approx 3$ K at the surface to $\Delta T \approx 20$ K in the stratosphere, implying a superrotational, global cyclostrophic circulation analogous to that observed on Venus[3]. Scaling for a hydrostatic, gradient-balanced flow suggested that the meridional and vertical winds should be much weaker than the zonal motion. Titan-specific general circulation models (GCMs) have since been introduced to study the conditions necessary for generation of atmospheric superrotation[6–9].

Observational evidence for winds on Titan has also been inferred from the finite oblateness of surfaces of constant pressure determined from precise ground-based astrometry during stellar occultations in 1989 and 2001[10,11]. These occultation experiments, as well as the thermal gradient observations, cannot be used to determine the sense of the zonal winds (that is, prograde or retrograde). A technique offering a direct determination of the wind velocity is to measure the differential Doppler shift of atmospheric spectral features as the field-of-view moves from east limb to west limb. Infrared heterodyne observations of Titan's ethane emission at 12 μm have yielded evidence for prograde winds with velocities exceeding 200 m s^{-1} but with a relatively large uncertainty of ±150 m s^{-1} (ref. 12). These results assume a global-average zonal wind field and apply to only a limited range in height near the 1 hPa level (200 km altitude). More traditional cloud-tracking techniques using Voyager 1 and ground-based images of Titan have been largely stymied by the ubiquitously poor image contrast. The success of such efforts has improved with the extended capabilities of the imaging system on Cassini, from which a number of atmospheric features have been identified as middle- to lower-tropospheric clouds, particularly near Titan's southern pole[13].

The Huygens probe entered and descended for nearly 150 min through the atmosphere of Titan, survived impact on the surface, and continued its telemetry broadcast to the Cassini spacecraft on two separate radio links, denoted channels A and B, for an additional 193 min (ref. 5). The Doppler Wind Experiment (DWE) instrumentation—consisting of an atomic rubidium oscillator in the probe transmitter to assure adequate frequency stability of the radiated signal and a similar device in the orbiter receiver to maintain the high frequency stability—was implemented only in channel A (2,040 MHz)[4]. Whereas channel B (2,098 MHz) functioned flawlessly during the entire mission, the channel A receiver was not properly configured during the probe relay sequence. All data on channel A, including the probe telemetry and the planned DWE measurements, were thus lost.

The channel A signal was monitored on Earth during the Huygens mission at fifteen radio telescopes, six of which recorded ground-based DWE measurements of the carrier frequency. Details on the

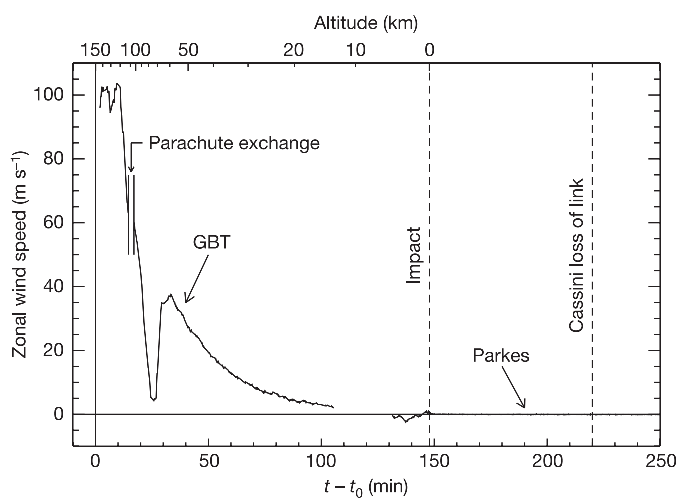

Figure 1 | Zonal wind velocity during the Huygens mission. The winds aloft are strictly prograde (positive zonal wind), but a significant reduction in the wind speed is observed at altitudes in the interval from 60 km to beyond 100 km. A one-minute interval associated with the parachute exchange, for which a more accurate determination of the actual descent velocity is necessary, has been excluded from this preliminary analysis. A monotonic decrease in the zonal wind speed is recorded from 60 km down to the end of the GBT (Green Bank Telescope) track at 10:56 SCET/UTC. The Parkes observations (from the Parkes Radio Telescope) could not begin until 11:22 SCET/UTC, thereby excluding wind determinations at heights from roughly 5 to 14 km. By this time Huygens was in a region of weak winds ($|U| \approx 1$ m s^{-1}) that display distinct structure with a trend towards retrograde motion. The 26-min gap between GBT and Parkes may be closed later with additional Doppler measurements from participating radio telescopes located in the intervening longitude range, compare Supplementary Table 1. t_0 indicates the time of the start of descent.

[1]Radioastronomisches Institut, Universität Bonn, Auf dem Hügel 71, 53125 Bonn, Germany. [2]NASA Goddard Institute for Space Studies, 2880 Broadway, New York, New York 10025, USA. [3]Jet Propulsion Laboratory, California Institute of Technology, 4800 Oak Grove Drive, Pasadena, California 91109, USA. [4]Department of Electrical & Computer Engineering, University of Idaho, Moscow, Idaho 83844-1023, USA. [5]Joint Institute for VLBI in Europe, PO Box 2, 7990 AA Dwingeloo, The Netherlands. [6]Institut für HF-Technik, Universität Bochum, 44780 Bochum, Germany. [7]Elektrotechnisches Institut, Technische Universität Dresden, 01062 Dresden, Germany. [8]Center for Radar Astronomy, Stanford University, Stanford, California 94305, USA.

participants in the radio astronomy segment of the Huygens mission, the observation campaign, and plots of the raw data are given in Supplementary Information. Only the data sets from the NRAO Robert C. Byrd Green Bank Telescope (GBT) in West Virginia and the CSIRO Parkes Radio Telescope in Australia have been processed for this initial report.

Starting with the raw Doppler measurements, it is essentially a geometric exercise to derive the motion of the transmitter in the Titan frame of reference. Motion of the Huygens probe in the vertical direction is measured *in situ* by many different instruments, primarily pressure sensors[14], but also by the Huygens radar altimeters. The consolidated measurements are processed iteratively by the Huygens Descent Trajectory Working Group (DTWG) to produce a series of continually improving probe trajectories referenced to Titan, including the descent velocity profile required for the present analysis[5]. The results presented here are based on DTWG data set no. 3, released in May 2005. The DTWG, based on knowledge of the Huygens trajectory to the point of atmospheric entry, also supplies the estimated spatial coordinates of the Huygens probe in latitude (10.33 ± 0.17° S), longitude (196.08 ± 0.25° W) and altitude (154.8 ± 11.2 km) at the start of descent, time t_0.

Two key assumptions about the horizontal motion of the probe simplify the problem. The first of these is that the horizontal drift of the probe follows the horizontal wind with a negligible response time. The actual response time for the Huygens descent system is estimated to be roughly 30–40 s in the stratosphere, decreasing to 3–5 s in the lowest 10 km (ref. 15). It follows that this first assumption may be fulfilled only marginally during the early minutes of the descent and during the change to a smaller (stabilizer) parachute at $t = t_0 + 15$ min ('parachute exchange'). The second assumption, that the drift in the meridional (north–south) direction is negligible, is based on theoretical considerations that imply dominance of the zonal (east–west) atmospheric circulation[3,6–9]. Under these conditions one is able to eliminate all other known contributions to the measured Doppler shift and determine the one remaining unknown, the zonal wind velocity. In addition to the above mentioned descent velocity, which slowly decreases with decreasing altitude, small, nearly constant, corrections must be applied for the effect of special relativity (−7.5 Hz, where the minus sign means a red shift), as well as the effects of general relativity associated with the Sun (18.2 Hz), Saturn (−0.7 Hz), Earth (1.4 Hz) and Titan (−0.08 Hz). Propagation corrections to the Doppler measurements from the neutral and ionized intervening media (Titan, interplanetary, Earth) have been estimated and found to be negligible. Finally, a small correction of +10.0 Hz was applied to the absolute transmission frequency by requiring that Huygens remain stationary on Titan's surface after landing. This residual is within the error limits of the pre-launch unit-level calibration of +9.2 Hz determined for the specific DWE rubidium oscillator unit used to drive the Huygens channel A transmitter.

The zonal wind derived from the ground-based Doppler data is shown in Fig. 1 as a function of time. More precisely, this quantity is the horizontal eastward velocity of Huygens with respect to the surface of Titan (with a positive value indicating the prograde direction). The time-integrated wind measurement from t_0 yields an estimate for the longitude of the Huygens landing site on Titan, 192.33 ± 0.31° W, which corresponds to an eastward drift of 3.75 ± 0.06° (165.8 ± 2.7 km) over the duration of the descent. Unfortunately, because of the slow rotation of Titan and the fact that the Earth was near zenith as viewed by Huygens, the Doppler data recorded after landing are not considered suitable for a more precise determination of the Huygens longitude.

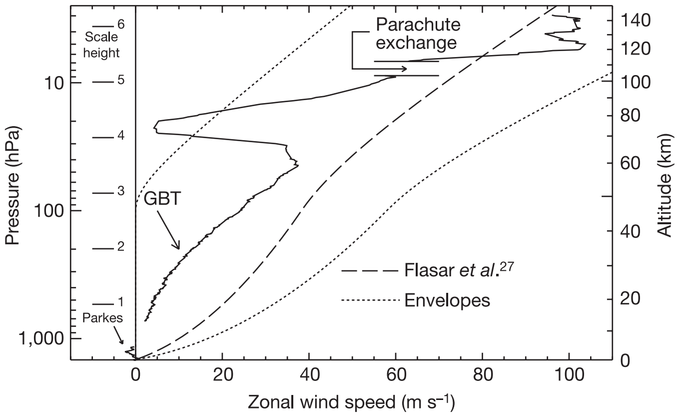

Figure 2 | Titan zonal wind height profile. The zonal wind derived from GBT and Parkes observations is compared with the prograde Titan engineering wind model and envelopes based on Voyager temperature data[27]. The estimated uncertainties in the zonal wind speed, based on an adaptation of an error analysis for the Huygens-Cassini link[28], are of the order of 80 cm s^{-1} at high altitude and drop roughly in proportion to the absolute speed to 15 cm s^{-1} just above the surface. These uncertainties are primarily systematic errors associated with the Huygens trajectory at entry. The estimated statistical (measurement) error is always smaller, the standard deviation being of the order of $\sigma \approx 5$ cm s^{-1} towards the end of descent. With the possible exception of the region above 100 km, where the wind fluctuations are greatest, the zonal flow is found to be generally weaker than those of the model. The wind shear layer in the height range between 60 and beyond 100 km was unexpected and is at present unexplained.

The variation of the zonal wind with altitude and pressure level is shown in Fig. 2. The measured profile roughly agrees with the upper level wind speeds anticipated by the engineering model, and is generally prograde above 14 km altitude. Assuming this local observation is representative of conditions at this latitude, the large prograde wind speed measured between 45 and 70 km altitude and above 85 km is much larger than Titan's equatorial rotation speed ($\Omega a \approx 11.74$ m s^{-1}, where $\Omega = 4.56 \times 10^{-6}$ rad s^{-1} and $a = 2{,}575$ km are Titan's rotation rate and radius, respectively), and thus represents the first *in situ* confirmation of the inferred superrotation of the atmosphere at these levels, as anticipated from the Voyager temperature data[3]. Moreover, the measured winds are consistent with the strong winds inferred from ground-based data under the assumption of cyclostrophic balance[10–12].

The most striking departure of the measured profile from the engineering model is the region of strong reversed shear between 65 and 75 km altitude (approximately 40 and 25 hPa, respectively), where the speed decreases to a minimum of 4 m s^{-1}, which then reverts to strong prograde shear above 75 km. This feature of Titan's wind profile is unlike that measured by any of the Doppler-tracked probes in the atmosphere of Venus[16].

Table 1 | Predictions of Titan's meteorology and DWE results

Prediction/model feature	DWE result	References
Atmospheric superrotation ($U \gg 12$ m s^{-1})*	Verified for upper troposphere and stratosphere	3, 6–8
Prograde (eastward) flow ($U > 0$)	Verified for all levels above 15 km (GBT data)	6–8, 23, 24
Isolated reversed shear ($\partial U/\partial z < 0$) within lower stratosphere	Verified, but stronger than simulated at 65–75 km, with Ri ≈ 2	7–9
Geostrophic ($U \ll 12$ m s^{-1}) sub-layer near surface	Verified and deeper than anticipated (more than ~1 scale height)	7–9, 25
Very weak surface winds	Verified ($\|U\| \approx 1$ m s^{-1})	23, 25
Warmer-poleward near-surface temperature in southern hemisphere	Consistent with geostrophic balance of upward-westward shear of low-level winds	18, 26

*U = zonal wind velocity.

The preliminary wind data shown in Fig. 2 have provided an *in situ* test of several Titan weather predictions, as summarized in Table 1. The verification of a superrotating atmosphere (in which the zonal wind velocity U is faster than the solid surface beneath it) definitively places Titan's meteorology in the same regime as that of Venus. The confirmed prograde direction of the flow lends further evidence for dynamical control of the cyclostrophic thermal structure. The isolated, reverse vertical shear region in the lower stratosphere, while not expected by the Huygens science team, appears to be present as a similar, but weaker, structure in Titan GCM simulations of this region[7–9]. We estimate that the implied Richardson number is as small as Ri $\approx$ 2–5 near the 30 hPa level. Earlier studies have shown that potential vorticity mixing within atmospheric regions where Ri $\approx$ 2 imposes a relatively flat variation of wind velocity over latitude, as compared with the rapid poleward increase of wind wherever Ri is large[17].

Although models and theory have anticipated a geostrophic sublayer, where the atmospheric flow is much slower than Titan's surface rotation speed, it is interesting that this appears to extend more than one scale height above the surface. This contrasts with the engineering wind model, which suggests a stronger vertical shear near the surface, and raises the interesting possibility of a more Earth-like weather regime within Titan's lower troposphere, perhaps including an alternation of low- and high-pressure centres and some meridional motion there. Surface winds are measured to be weak ($|U| \approx 1\,\mathrm{m\,s^{-1}}$), as expected. The vertical wind shear in the lowest part of the troposphere, with increasing westward flow with altitude, implies (via the thermal wind equation) a geostrophically balanced warmer-poleward temperature structure near the surface. Although some caution must be applied to a global interpretation of the available single-latitude measurement, this feature of the DWE profile would be consistent with the relatively warm southern (summer) pole, which is considered to be the underlying reason for the convective cloud features observed there[18].

It will be of great interest to see if these inferences from comparisons between the models and the measured DWE profile are corroborated by the vertical-latitudinal sounding of temperatures within the 10–50 hPa region by the Cassini Composite Infrared Spectrometer (CIRS) instrument[19,20]—or by the pressure/temperature versus height profiles down to the surface derived from Cassini radio science measurements[21] during the upcoming Titan occultations.

The ambiguity between contributions from zonal and meridional winds, at least near the surface, has essentially been resolved by a detailed comparison with wind drift data from the Descent Imager/Spectral Radiometer (DISR) instrument[22]. The current DISR analysis indicates that Huygens drifted roughly westward during the last 7 km of descent. This is consistent with the small, but predominantly retrograde, zonal wind determinations from the Parkes Doppler data recorded during the 15 min before landing on Titan.

As seen in Fig. 2, there is a data gap of less than a half scale-height between the region of smooth eastward flow above 14 km and the apparently more structured, but very weak, wind regime ($U < 2\,\mathrm{m\,s^{-1}}$) from 5 km down to the surface. A future report should be able to address this transition on the basis of further Doppler data from the other ground-based radio telescopes (see Supplementary Information). In addition, the simultaneously recorded Very Long Baseline Interferometry (VLBI) measurements of the position of the probe on the sky should eventually allow the assumption of purely zonal flow to be dropped. A combined Doppler/VLBI solution would then yield the full two-dimensional horizontal wind profile during the Huygens descent.

Received 20 May; accepted 20 July 2005.
Published online 30 November 2005.

1. Tyler, G. L. *et al.* Radio science investigations of the Saturn system with Voyager 1: Preliminary results. *Science* **212,** 201–206 (1981).
2. Lindal, G. F. *et al.* The atmosphere of Titan: An analysis of the Voyager 1 radio occultation measurements. *Icarus* **53,** 348–363 (1983).
3. Flasar, F. M., Samuelson, R. E. & Conrath, B. J. Titan's atmosphere: temperature and dynamics. *Nature* **292,** 693–698 (1981).
4. Bird, M. K. *et al.* The Huygens Doppler Wind Experiment. *Space Sci. Rev.* **104,** 613–640 (2002).
5. Lebreton, J.-P. *et al.* An overview of the descent and landing of the Huygens probe. *Nature* doi:10.1038/nature04347 (this issue).
6. Del Genio, A. D., Zhou, W. & Eichler, T. P. Equatorial superrotation in a slowly rotating GCM: Implications for Titan and Venus. *Icarus* **101,** 1–17 (1993).
7. Hourdin, F. *et al.* Numerical simulation of the general circulation of the atmosphere of Titan. *Icarus* **117,** 358–374 (1995).
8. Tokano, T., Neubauer, F. M., Laube, M. & McKay, C. P. Seasonal variation of Titan's atmospheric structure simulated by a general circulation model. *Planet. Space Sci.* **47,** 493–520 (1999).
9. Luz, D., Hourdin, F., Rannou, P. & Lebonnois, S. Latitudinal transport by baroclinic waves in Titan's stratosphere. II. Results from a coupled dynamics-microphysics-photochemistry GCM. *Icarus* **166,** 343–358 (2003).
10. Hubbard, W. B. *et al.* The occultation of 28 Sgr by Titan. *Astron. Astrophys.* **269,** 541–563 (1993).
11. Bouchez, A. H. *Seasonal Trends in Titan's Atmosphere: Haze, Wind and Clouds* PhD thesis, California Inst. Technol. (2003); available at ⟨http://www.gps.caltech.edu/~antonin/thesis⟩.
12. Kostiuk, T. *et al.* Direct measurement of winds on Titan. *Geophys. Res. Lett.* **28,** 2361–2364 (2000).
13. Porco, C. C. *et al.* Imaging of Titan from the Cassini spacecraft. *Nature* **434,** 159–168 (2005).
14. Fulchignoni, M. *et al. In situ* measurements of the physical characteristics of Titan's atmosphere. *Nature* doi:10.1038/nature04314 (this issue).
15. Atkinson, D. H., Pollack, J. B. & Seiff, A. Measurement of a zonal wind profile on Titan by Doppler tracking of the Cassini entry probe. *Radio Sci.* **25,** 865–882 (1990).
16. Counselman, C. C. III, Gourevitch, S. A., King, R. W. & Loriot, G. B. Zonal and meridional circulation of the lower atmosphere of Venus determined by radio interferometry. *J. Geophys. Res.* **85,** 8026–8030 (1980).
17. Allison, M., Del Genio, A. D. & Zhou, W. Zero potential vorticity envelopes for the zonal-mean velocity of the Venus/Titan atmospheres. *J. Atmos. Sci.* **51,** 694–702 (1994).
18. Brown, M. E., Bouchez, A. H. & Griffith, C. A. Direct detection of variable tropospheric clouds near Titan's south pole. *Nature* **420,** 795–797 (2002).
19. Flasar, F. M. *et al.* Exploring the Saturn system in the thermal infrared: The Composite Infrared Spectrometer. *Space Sci. Rev.* **115,** 169–297 (2004).
20. Flasar, F. M. *et al.* Titan's atmospheric temperatures, winds, and composition. *Science* **308,** 975–978 (2005).
21. Kliore, A. J. *et al.* Cassini radio science. *Space Sci. Rev.* **115,** 1–70 (2004).
22. Tomasko, M. G. *et al.* Rain, winds and haze during the Huygens probe's descent to Titan's surface. *Nature* doi:10.1038/nature04126 (this issue).
23. Flasar, F. M. & Conrath, B. J. in *Proc. Symposium on Titan* (ed. Kaldeich, B.) 89–99 (ESA-SP 338, ESA Publications, ESTEC, Noordwijk, The Netherlands, 1992).
24. Del Genio, A. D. & Zhou, W. Simulations of superrotation on slowly rotating planets: Sensitivity to rotation and initial condition. *Icarus* **120,** 332–343 (1996).
25. Allison, M. in *Proc. Symposium on Titan* (ed. Kaldeich, B.) 113–118 (ESA SP-338, ESA Publications, ESTEC, Noordwijk, The Netherlands, 1992).
26. Tokano, T. Meteorological assessment of the surface temperatures on Titan: Constraints on the surface type. *Icarus* **173,** 222–242 (2005).
27. Flasar, F. M., Allison, M. & Lunine, J. I. in *Huygens Science Payload and Mission* (ed. Wilson, A.) 287–298 (ESA-SP 1177, ESA Publications, ESTEC, Noordwijk, The Netherlands, 1997).
28. Dutta-Roy, R. & Bird, M. K. in *Planetary Probe Atmospheric Entry and Descent Trajectory Analysis and Science* (ed. Wilson, A.) 109–116 (ESA SP-544, ESA Publications, ESTEC, Noordwijk, The Netherlands, 2004).

Supplementary Information is linked to the online version of the paper at www.nature.com/nature.

Acknowledgements This Letter presents results of a research project partially funded by the Deutsches Zentrum für Luft- und Raumfahrt (DLR). Parts of the research described here were carried out by the Jet Propulsion Laboratory, California Institute of Technology, under contract with NASA, and by NASA's Goddard Institute for Space Studies. We thank R. Kohl, K.-P. Wagner and M. Heyl for their efforts during the DWE development programme. We appreciate the support provided by the National Radio Astronomy Observatory (NRAO) and the Australia Telescope National Facility (ATNF). NRAO is operated by Associated Universities, Inc., under a cooperative agreement with the NSF. The ATNF, managed by the Commonwealth Scientific and Industrial Research Organization (CSIRO), is funded by the Commonwealth of Australia.

Author Information Reprints and permissions information is available at npg.nature.com/reprintsandpermissions. The authors declare no competing financial interests. Correspondence and requests for materials should be addressed to M.K.B. (mbird@astro.uni-bonn.de).