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# Wind shear and turbulence on Titan: Huygens analysis

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ABSTRACT

Wind shear measured by Doppler tracking of the Huygens probe is evaluated, and found to be within the range anticipated by pre-flight assessments (namely less than two times the Brunt–Väisälä frequency). The strongest large-scale shear encountered was ~5 m/s/km, a level associated with 'Light' turbulence in terrestrial aviation. Near-surface winds (below 4 km) have small-scale fluctuations of ~0.1 m/s on 1 s timescales, indicated both by probe tilt and Doppler tracking, and the characteristics of the fluctuation, of interest for future missions to Titan, can be reproduced with a simple autoregressive (AR(1)) model. The turbulent dissipation rate at an altitude of ~500 m is found to be ~0.2 $cm^2/s^3$, which may be a useful benchmark for atmospheric circulation models.

## 1. Introduction

Wind shear, the spatial gradient of wind speed, is of significant practical interest in planetary exploration and in terrestrial aviation. A vehicle moving relative to the air will encounter time-varying winds which can excite movements which may blur images (Karkoschka, 2016; Lorenz, 2010), affect the strength of the radio signal (Dzierma et al., 2007), or cause air passengers to spill their drinks. These movements, which depend on the characteristics of the vehicle as well as the wind shear, are typically referred to as 'turbulence'. Turbulence more generally, however, is the spatio-temporal variation of the wind, and can also manifest itself as fluctuations in a time series of wind measured at a fixed point as the turbulent wind field is advected past a meteorological station. These fluctuations are of interest in that they are intimately associated with the transport of matter, energy and momentum at the macroscale through an atmosphere via so-called eddy diffusivity. Turbulent fluctuations are often also the critical factor in exceeding a transport threshold where mean winds are not enough (e.g. the saltation speed for sand grains – Burr et al., 2015; Lorenz, 2014; Tokano, 2010). The fluctuations also represent the process by which mechanical energy is ultimately dissipated by the turbulent cascade into viscous dissipation.

Here I explore what the Huygens descent measurements indicate about these topics, most particularly through the wind measurements made by the Doppler Wind Experiment (Bird et al., 2005; Folkner et al., 2006). First, however, it is pertinent to recall what kind of wind shear environment was anticipated.

## 2. Pre-Cassini expectations of wind shear

Because the gust environment could excite motions of the Huygens probe under its parachute, thereby causing an interruption of its radio link to Cassini by mispointing its antennas, an evaluation of wind shear was made during the Huygens probe development (Strobel and Sicardy, 1997). Having to devise a specification on some aspect of a planetary environment for a vehicle intended to make the very first in-situ measurements of that environment is one of the great ironical challenges of planetary exploration (see e.g. Chen et al., 2010; Lorenz et al., 2012). The evaluation by Strobel and Sicardy (1997) identified physical constraints on wind shear (specifically, the vertical gradient of horizontal winds), suggesting that a strong upper limit on shear determined by the critical Richardson number (Ri~0.25) was 2N, where N is the Brunt–Väisälä (buoyancy) frequency, determined by the vertical stability of the atmosphere. (They also discuss shear from gravity wave-breaking, determining this to be of order ~N, but retained 2N as providing comfortable margin.) Although not intuitively obvious, it is seen that the buoyancy frequency units of inverse seconds are the same as those of wind shear, namely meters per second per meter. The buoyancy frequency profile was estimated from the temperature structure derived for Titan's low-latitude atmosphere from the Voyager 1 radio occultation experiment. The peak shear (2N) anticipated from this calculation was 16 m/s/km at an altitude of 60 km. As this paper shows later, this estimate, devised from very limited information, proved to be a generally appropriate one.

In flowing down this expectation of the maximum possible shear to a parachute engineering specification (Table 1, from Collet, 1997), the profile was de-rated somewhat by 'engineering

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judgment'. This was presumably because it was hard to meet the underlying requirement that "the probe shall limit the pendular (sic) motion during the descent to an amplitude of 10°" in that in steady state descent at speed W, if the wind shear is $\gamma$, then the probe-parachute system will trim at an angle $\Theta$ given by $\tan(\Theta)=W\gamma/g$. Since the terminal velocity W at 60 km is 25 m/s, adopting the upper limit of 2N would give a trim of 16° - thus even with a parachute system that was perfectly damped, the allowed limit would be violated. The specification was therefore rationalized by cutting off the peak and reducing the profile overall. The specification was considered a '95%' limit (without documented statistical justification, but with the intent that occasional violations could be tolerated).

## 3. Wind profile in the free atmosphere

The principal source of wind information on Titan is from the Doppler tracking of the Huygens probe (Bird et al., 2005; Folkner et al., 2006). The range-rate (i.e. velocity along the line-of-sight to the Earth) was measured using a precision frequency reference on the radio link. With knowledge of the viewing geometry and an estimate of the vertical descent speed of the probe (which had a significant projection on the line-of-sight) and with the assumption that meridional winds were zero, this range rate could be rescaled into a zonal (E-W) probe velocity, generally close to the ambient zonal wind velocity. The resultant dataset (HP-SSA-DWE-2-3-DESCENT-V1.0) is archived on the Atmospheres Node of the Planetary Data System.

In fact, the meridional velocity is not quite zero, and some initial estimates were made by computing the probe location relative to features seen on the ground by the Descent Imager and Spectral Radiometer (DISR) on Huygens during the latter part of descent (Tomasko et al., 2005). Recently, an improved evaluation of meridional winds has been made using the entire descent image dataset (Karkoschka, 2016). While these data are useful to define the overall wind profile (and indicate a shear of 1 m/s/km in the lowest 2 km of the atmosphere and very little shear above), they are too sparse to meaningfully evaluate fluctuations. The meridional wind speed is small enough that the assumption of zero in the reduction of the range rate measurement to a zonal wind speed is essentially unaffected.

The zonal wind profile is plotted on Fig. 1, and several broadly linear regions are identified, with large-scale (several km in vertical extent) shears of up to 5 m/s/km. This observed shear profile is plotted as grey bars in Fig. 2, which also shows the (doubled) buoyancy frequency from Strobel and Sicardy (1997) and the adopted specification from Table 1. It is seen that the specification was not violated, although there was essentially zero margin in the 110–120 km altitude range. The original recommendation of a robust upper limit of 2N would have had approximately 50% margin. For reference, an estimate of the recovered Richardson number profile is given in Appendix (Fig. A1).

To put these shears in context, although turbulence in passenger aviation is usually defined in terms of vehicle motion (and a light aircraft will typically respond more violently to a given change in wind speed than a heavy one), Houboldt's review paper on the topic (Houboldt, 1973) suggests that 'Light' turbulence is typically defined by a shear of 2.5–10 m/s/km. Thus some parts of the Huygens descent met this classification, but moderate or severe (>17.5 m/s/km) shear levels were not encountered.

## 4. Near-surface atmosphere profile

The atmosphere near the ground is considered separately from the free atmosphere: the stability of the Planetary Boundary Layer (PBL) makes its behavior quite distinct. The PBL is indicated in the potential temperature profile (temperature with an adiabatic correction for altitude) which shows a constant region up to 300 m altitude (Fig. 3). Although initially interpreted as defining 'the planetary boundary layer' (Tokano et al., 2006) this seems in fact merely to be the top of the growing diurnal boundary layer – the Huygens landing was at a local mean solar time of about 9:45 am.

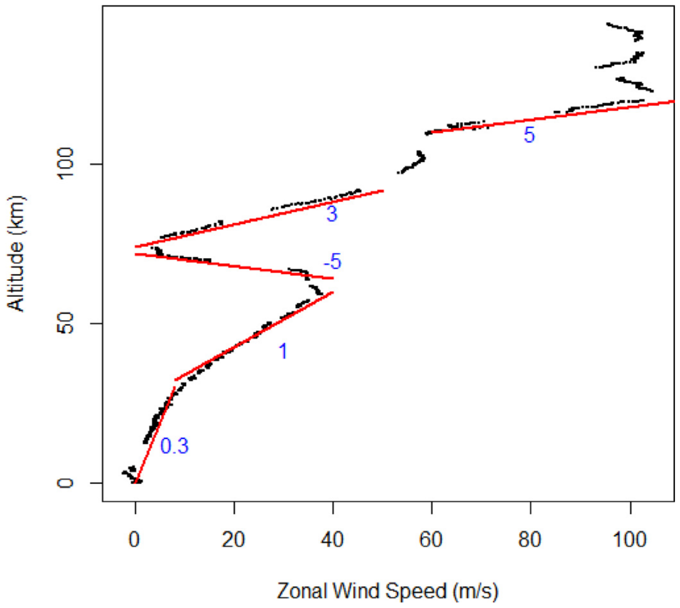

**Fig. 1.** The Huygens Doppler Wind profile (dots). Approximately linear regions of wind shear are shown as red line segments, with the gradient (in m/s/km) noted.

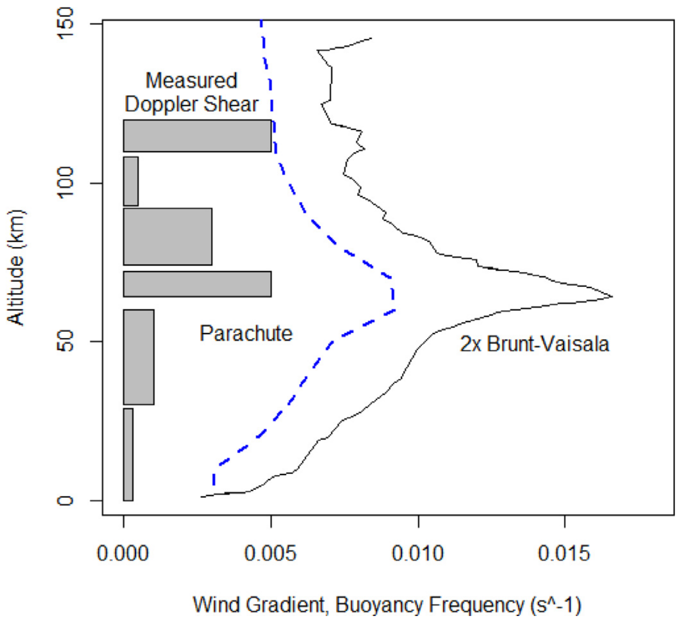

**Fig. 2.** The upper limit on expected wind shear defined in Strobel and Sicardy (1997, solid curve) as twice the Brunt–Väisälä frequency, compared with the adopted 95% Huygens wind shear specification (blue dashed curve, table 1) and the observed shear from the linear segments identified in Fig. 1 (grey bars). It is seen that in general the wind shear did not quite exceed the specification. It is of interest that one region of strongest observed shear (60–80 km) was where the shear was anticipated to be strongest. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Lorenz et al. (2010) noted that breaks in slope higher in the profile may in fact indicate the full depth of the layer relevant for near-surface atmospheric dynamics, and in particular breaks at 2 & 3 km (C and D) in figure may be responsible for controlling the