In-Situ Measurement of the Saltation Threshold of Titan's Sands with Downwash from a Rotorcraft Lander

Ralph D. Lorenz[1] [1]Johns Hopkins Applied Physics Laboratory, Laurel, MD 20723, USA (ralph.lorenz@jhuapl.edu)

Introduction: The precise conditions under which Titan's vast fields of organic sand dunes [1] were formed are unknown. Tokano [2] showed that the predicted dune orientations resulting from wind histories generated by a global circulation model were appreciably sensitive to the chosen saltation threshold speed. Knowledge of this parameter would be valuable for the interpretation not only of the orientation of the dunes, but estimates for their construction and reorientation timescales and ultimately the origin of the sand itself [3]. However, without knowledge of what the sand actually is and how it behaves under Titan conditions, these interpretations – however elaborate the circulation models driving them [4,5] – must be considered uncertain.

Threshold Estimates : As reviewed by Lorenz [6], the freestream windspeed corresponding to the saltation threshold on Titan is likely just over 1 m/s (a friction speed – a measure of wind stress – of ~0.04 m/s) – see figure 1. This follows from applying terrestrial empirical expressions, with adjustment for sediment and atmospheric density, and Titan gravity (but with the implicit assumption that cohesion is similar for Titan and Earth sediments in their respective environments). Burr et al. [7] report some wind tunnel experiments that partly replicate Titan conditions and indicate higher speeds than some of these expressions. However, these experiments using lower-density materials to simulate low gravity only address part of the unsteady saltation physics.

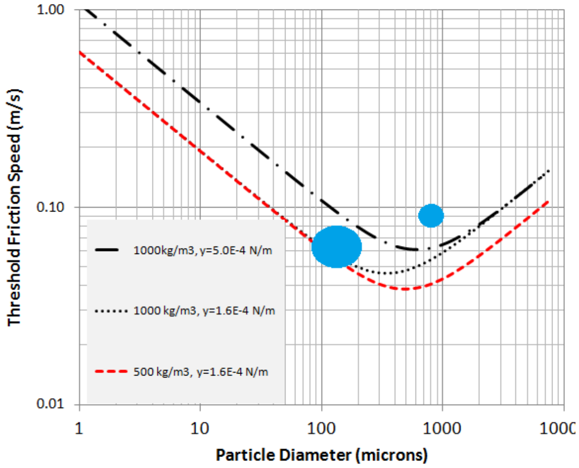

Fig. 1. Saltation threshold (friction speeds – for freestream windspeeds multiply by ~20) given uncertainties (curves) in composition and cohesion. Blue ellipses indicate measurements [7].

Furthermore, as noted in [6], triboelectric effects may be rather significant for Titan, since the atmospheric and surface electrical conductivity at the surface will be rather low.

Another effect at Titan that is challenging (as on Earth) is the possible role of varying methane/ethane moisture. Even a small amount of water moisture on Earth can modify the threshold speed appreciably [e.g. 8], and the sediment at the Huygens landing site was measured to be damp [9].

It would therefore be desirable to measure the tranport threshold in-situ on Titan. The Dragonfly relocatable lander (fig.2) being proposed by APL to the NASA New Frontiers program [10,11] offers such an opportunity.

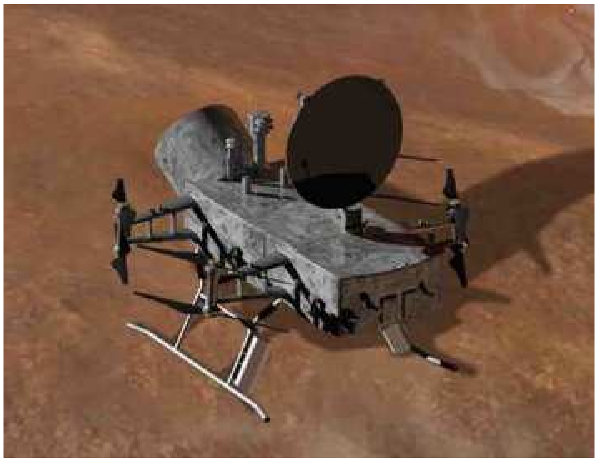

Fig. 2. Artist's impression of the Dragonfly relocatable lander. Outboard rotors allow the controlled application of wind stress to surface materials.

Threshold Measurement: The typical approach to measuring saltation threshold [8] is to apply a linear airflow across a sediment deposit in a wind tunnel, sometimes with upstream manipulation of the boundary layer velocity profile via roughness elements. Sometimes portable wind tunnels are deployed in the field to capture sediment characteristics not fully replicated in laboratory analog materials. A more convenient apparatus, the PI-SWERL [10], applies a wind stress to a surface by spinning an annular rotor (with radial supports) immediately above the surface inside an 'upturned-bucket' housing (an arrangement not unlike a lawnmower). Although a complex Couette-like shearing flow is produced internally, the net effect on sediment-lofting is quite reproducible and field comparisons show an excellent correlation of this method with portable wind tunnels [11].

This precedent suggests that flows imposed by other systems could provide useful threshold information. Notably, propulsion systems for soft-landing apply gas jets downwards which, especially in the case of rocket exhaust into vacuum or Mars' atmosphere, can erode the surface under the lander, as observed with Phoenix and Apollo.

On Titan, the dense atmosphere allows thrust for soft-landing (or indeed, flight) to be easily generated by wide rotors, producing much lower jet velocities and much less erosion.

Rotor Downwash: The characteristic downwash ('induced') velocity from a rotor is typically calculated from simple momentum considerations ($T=A\rho V^2$) using actuator disk theory. A vehicle on Titan (ρ=5.4 kg/m^3, g=1.35 ms^{-2}) with a loading (T/Ag) of about 100kg per rotor, with rotor area A of 1m^2, will have a downwash velocity of about 5 m/s.

This broad downwash jet will entrain air, widening and weakening with distance below the rotor plane. If the rotor plane is 1 rotor diameter above the surface, the outflow velocity will be approximately the same as the induced velocity.

In fact the interaction of rotor downwash with surface sediments has become a topic of intense study (e.g. [12,13]) in the context of recent military helicopter operations in deserts (notably Afghanistan) where dust-lifting at landing ("brownout") has caused some loss of pilot situational awareness. Field tests, flow visualization experiments, and Computational Fluid Dynamics (CFD) studies have been applied to the phenomenon.

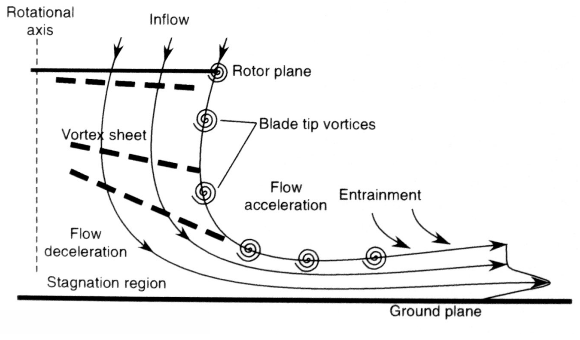

Fig.3. Schematic [13] of the flow structures beneath a rotor above a plane. The downwash turns and advects flow structures (e.g. tip vortices) and lofted sediments radially away from the vehicle.

Specifically, the sediment-raising appears more efficient than would be expected from simple uniform-jet effects. In particular, the vortices spiralling down [13] from the rotor blade tips (figure 3) give local velocity enhancements, and their unsteady shear stress applied to the ground initiates saltation and suspension.

These complications aside, as in the case of the PI-SWERL, it seems probable that the flow complexity can be calibrated out.

Experiment Implementation: As with the PI-SWERL, two broad classes of experiment can be imagined. In one, the rotor is spun at progressively higher speeds, imposing progressively higher wind stress on the surface (with the rotor loading described earlier, the imposition of a ~2m/s wind speed on the surface, likely above threshold, would produce a thrust of only about 5% of the vehicle weight if only a single rotor is powered, so such an experiment can be conducted safely on the surface without inadvertent take-off.) The threshold is deduced by observing at what speed sediment begins to move. This is relatively easy to determine with dedicated instrumentation (e.g. the PI-SWERL uses light-scattering sensors to measure suspended dust in real-time) : one possibility is to detect sediment movement via the production of triboelectric charging and its effect on local electric fields (e.g. [14]); another is to take images at successive intervals and detect motion via blurring or surface change. A second approach, yielding a less direct measure of threshold but a more direct measure of net transport, is to run the rotors at some specific power setting for an extended interval and observe net surface change (e.g. formation of scour around pebbles or similar).

Field experiments, supplemented by CFD, will permit the calibration of rotor rpm to imposed wind stress for single- or multiple-rotor experiments, and identify the most efficient observation approaches.

References: [1] Lorenz, R. D. et al., (2006) *Science*, 312, 724-727. [2] Tokano, T. (2008) *Icarus*, 194, 243-262 [3] Barnes, J. et al. (2015) *Planetary Science*, 4, 1-19 [4] Lucas et al. (2014). *Geophys. Res. Lett.* 10.1002/2014GL060971 [5] Charnay et al. (2015) *Nature Geoscience* 8, 362-266 [6] Lorenz, R. (2014) *Icarus*, 230, 162–167 [7] Burr, D. et al. (2015) *Nature*, 517, 63-66 [8] Lorenz, R. and J. Zimbelman, *Dune Worlds*, Springer, 2015. [9] Lorenz, R. (2006) *Meteoritics and Planetary Science*, 41, 1705-1711 [10] Turtle, E. et al. (2017) *LPSC XLVIII* #1958 [11] Barnes, J. et al. (2017) 5th Planetary Dunes Workshop [10] Etyemezian, V. et al. (2007) *Atmospheric Environment*, 41, 3789–3796 [11] Sweeney, M. et al. (2008) *J. Geophys. Res.* 113, F01012, doi:10.1029/2007JF000830 [12] Milluzzo, J. and J. G. Leishman (2010), *Journal of the American Helicopter Society*, 55, 032009 [13] Rauleder, J. and J. G. Leishman (2014), *AIAA Journal*, 52, 146-161 [14] Merrison, J. P. (2012) *Aeolian Research*, 4, 1-6