FIRST LANDING FOR DRAGONFLY: NAMIB, SAHARA AND ARABIAN DESERT ANALOGS FOR FLAT INTERDUNES ON TITAN.

R. D. Lorenz[1], J. W. Barnes[2], S. Mackenzie[1], C. D. Neish[3,4], J. Radebaugh[5], A. Le Gall[6], E. P. Turtle[1], D. S. Adams[1], J. W. Langelaan[7] and the Dragonfly Science Team [1]Johns Hopkins Applied Physics Laboratory, Laurel, MD. [2]University of Idaho, Moscow, ID. [3]Planetary Science Institute, Tucson, AZ. [4]University of Western Ontario, London, ON. [5]Brigham Young University, Provo, UT. [6]LATMOS, Paris, France. [7]Penn State University, University Park, PA.

Introduction: Titan is flat. While this is of course a generalization to which there are obvious exceptions, it is evident from the millions of topographic measurements [1] by *Cassini's* RADAR that the terrain height variations [2] on Titan are overall small compared with the terrestrial planets, and regional slopes are similarly modest.

Dragonfly: The most astrobiologically interesting areas on Titan (cryovolcanic flows and impact melt sheets [3]) may have complex terrain, but a mission with aerial mobility such as Dragonfly [4,5] has the capability to reconnoiter these areas before committing to landing there.

The 2007 APL-led Titan Flagship [6] study (which outlined much of the science background pursued by Dragonfly) designated the Belet equatorial sand sea as a large, safe target landing zone that would be relatively clear of rock and gully hazards. This study was initiated before Titan's seas of liquid hydrocarbons were mapped and before significant developments in sensors and Terrain-Relative Navigation (TRN) in support of lunar and martian landing systems (e.g. APL/MSFC Mighty Eagle [7]). The study defined a Pathfinder-like lander which would roll down any dune slopes in its airbags and open its petals at the base of the dune.

Dunes/Interdunes: Within a more modern framework where terrain can be assessed in real-time by a lander, Titan's sand seas still remain the best landing terrain – they are widespread around the equator and so offer proximal access to high-priority targets, and their terrain characteristics are well-understood via terrestrial analogs (*e.g.*, Figures 1-3). In particular, the large linear dunes of the type discovered [8] on Titan are characteristic [9] of the Namib and Arabian deserts, and the Great Sand Sea (Eastern Sahara). Although these deserts feature some of the largest dunes on Earth, in fact wide interdunes (typically 1-3 km, as on Titan) are typically flat enough to allow even fixed-wing aircraft to safely land.

Dragonfly would begin rotor flight in a north-south direction after parachute separation: this traverse will be guaranteed to span dune/interdune areas known from *Cassini* synthetic aperture radar (SAR) imaging (the dunes are in a predominantly E-W orientation). When a flat area is detected, the vehicle lands autonomously. After the first landing, the vehicle can take off to survey potential target areas and return to the first known safe site. An obvious first target after sampling interdune material (typically gravel) is the pure sand composition of shallow dune plinths, likely accessible on ~1-km scales [10].

Figure 1: (top) Aerial view of the north part of the Namib Sand Sea, with linear dunes that are the archetype in height, width and morphology of those on Titan. 1-2 km wide and flat interdune areas are evident. An aerial system with >2-km crossrange capability and terrain roughness assessment will have no difficulty finding a safe landing spot in this landscape. (bottom) Field photo from an interdune area further south near Sossusvlei – note that tree hazards are not expected on Titan.

Figure 2: View from dune crest near the United Arab Emirates side of the UAE/Oman border (border fence is ~5-m tall) at the edge of a field of giant linear dunes in the Arabian desert. A few shallow barchans litter the flat interdune floor, although these and the steep linear dunes occupy only a small area fraction. The compositional distinction between the red dune sands and the white limestone gravels in the interdunes is especially apparent in this afternoon view at >90 degree phase angle.

Figure 3: (top) Kiteborne camera view of Ghard el Quattaniya linear dunes west of Cairo, Egypt showing dune and plinth. (bottom) Field photo at same dune showing Ground Penetrating Radar operations. While dune slopes themselves would be avoided, it is clear that shallow-sloped dune plinths can allow safe access to sand material.

Landing slope tolerance: The specification of conventional helicopters (e.g. Robinson R-22) typically allows for terrain slopes of 10° with uphill or sideways slopes allowed to be larger (e.g. 15° for UH-60 Blackhawk) as the tail rotor is usually the limiting factor. Dragonfly's compact quad configuration will likely permit landing on even larger slopes; in any case 10° appears a representative conservative capability, typical for planetary landers (e.g. Apollo [11]). There should be no difficulty in finding areas with slopes considerably shallower than this in dune environments (Figure 4).

Cassini Data: In addition to pure analogy, recognizing terrain type from SAR images and using terrestrial examples as a guide, *Cassini* data at Titan can offer direct measurements useful for landing site characterization. Even at low spatial resolution, radar data is sensitive to slope distributions at wavelength and larger scales (and indeed groundbased radar data was a key input for the successful *Viking* landing site assessment [12] for which little high-resolution image data were available). *Cassini* altimetry and SARtopo [13,14] can measure slopes at ~10-km scales (in fact non-zero large-scale slopes assure good drainage). SAR stereo and radarclinometry can indicate sub-km-scale slopes (e.g. [15] found average dunefield slopes of 4-6^{o} with standard deviations of 2-3^{o}, even in areas with the most abundant sand and thus the highest dunes). Altimeter echo modeling [16], radarclinometry [8,15] and near-infrared photoclinometry [17] indicates dune heights of a few tens of m to ~150m, similar to the analogs in this abstract. Modeling of radar backscatter can also constrain decimeter-scale slope distributions, (e.g. [18] showed surface roughness of <1-cm). Indeed, the *Huygens* radar altimeter backscatter on Titan resembled that of the flat airfields from which balloon tests were flown on Earth [19].

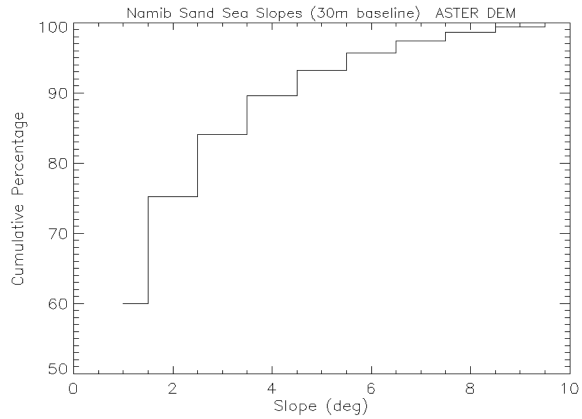

Figure 4: N-S and E-W point-point slopes (30-m spacing from ASTER stereo DEM) in the Namib sand sea. The steep dunes themselves occupy only a small area fraction - 99% of slopes are less than or equal to 10^{o} and 95% are less than or equal to 6^{o}.

Conclusions: Interdune areas represent some of the most lander-friendly natural terrain on planetary surfaces. While Titan lacks the high-resolution imaging coverage we have become used to at Mars, the particular ability of radar data to characterize terrain on lander-relevant scales gives assurance of safe landing zones at Titan. Dragonfly has the capability to find a patch of terrain it can land on over ranges much larger than Titan's dune spacing; analogs and *Cassini* data suggest such patches will be large and abundant.

References: [1] Lorenz R. et al. (2013), *Icarus*, 225, 367-377 [2] Lorenz R. et al. (2011), *Icarus*, 211, 699-706 [3] Neish C.D. *et al.* (2018) *Astrobiology* in press. [4] Turtle E.P. *et al.* (2018) *LPSC 49*. [5] Lorenz R.D. *et al.* (2017) *APL Tech Digest*, in press [6] Leary J. *et al.* (2008) https://solarsystem.nasa.gov/multimedia/downloads/Titan_Explorer_Public_Report_FC_opt.pdf. [7] McGee, T. et al. (2013) *APL Tech Digest*, 32, 619-635 [8] Lorenz R.D. *et al.* (2006) *Science*, 312, 724-727 [9] Radebaugh, J. *et al.* (2010) *Geomorphology*, 121, 122-132 [10] Barnes, J. *et al.* (2018) *LPSC 49*. [11] Walton, W. *et al*. (1964) *J. Spacecraft & Rockets*, 1, 552-556 [12] Masursky, H. and N. Crabhill (1976) *Science*, 193, 809-812 [13] Zebker, H. et al. (2009) *Icarus*, 200, 240-255 [14] Stiles, B. *et al.* (2009) *Icarus*, 202, 584-598 [15] Neish, C. D. et al. (2010) *Icarus*, 208, 385-394 [16] Mastrogiuseppe, M. et al. (2014), *Icarus* 230, 191-197 [17] Barnes, J. et al. (2008) *Icarus* 195, 400-414 [18] Paillou, Ph. et al. (2014) *Icarus*, 230, 208-214 [19] Lorenz, R. *et al.* (2016) *Icarus*, 270, 248-259