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Global pattern of Titan's dunes: Radar survey from the Cassini prime mission

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[1] We present a map of the orientation and extent of Titan's sand dunes derived from the complete radar imaging dataset from the Cassini prime mission. The 16,000 dune segments we have mapped cover ~8% of the Titan's surface (suggesting a total coverage of ~20%), are confined within 30° of the equator, and show local and regional deviations of dune orientation of up to about 40° from due Eastwards. There is no obvious global longitudinal pattern, although some divergence with latitude is apparent. The most striking pattern is one of collimation by and divergence around bright and/or high terrain. Obstacles 100–300 m high obstruct dunes when the local slope is 1/50 or steeper, while slopes 1/200 or shallower cause dunes to thin out as they climb, or to deviate around the obstacles. **Citation:** Lorenz, R. D., and J. Radebaugh (2009), Global pattern of Titan's dunes: Radar survey from the Cassini prime mission, *Geophys. Res. Lett.*, *36*, L03202, doi:10.1029/2008GL036850.

1. Introduction

[2] Titan's dark equatorial regions have been found in imaging radar observations by Cassini [*Lorenz et al.*, 2006] to be covered in vast seas of giant linear dunes, made of dark, likely photochemically-derived, material. This discovery confounded earlier expectations [*Lorenz et al.*, 1995] that Titan would lack adequate winds or sand-generation processes, or that liquids on Titan would trap sand ('sand' in this context is a particle-size classification, the material itself being icy or organic). Some dunes have also been observed in the near-infrared by Cassini's VIMS (Visual and Infrared Mapping Spectrometer [*Barnes et al.*, 2008]), which showed that interdune areas were clear of sand, suggesting the dunes maybe active today. An initial survey by us [*Radebaugh et al.*, 2008] examined data from Cassini flybys T3–T19 (February 2005–October 2006), noting many thousands of individual dunes, interpreted to be longitudinal, with mean lengths of the order of 50 km. That work suggested that the dunes cover about 40% of the equatorial half of Titan's surface area, forming a significant inventory of organic material [*Lorenz et al.*, 2008], and that the dunes are almost entirely oriented close to due Eastwards based on morphology (see section 2); the dune morphologies are compared with terrestrial analogs of *Radebaugh et al.* [2009]. Here we report a more complete survey, covering all the Synthetic Aperture Radar (SAR) imagery acquired through the Cassini prime ('nominal') mission (through T44, June 2008) covering 27% of Titan's surface.

[3] The presence of dunes requires mobile (i.e., dry) sand-sized particulates, as well as winds strong enough to move them. On the first criterion, sand may or may not be present at all latitudes, but modeling of the Hadley circulation on Titan and the transport of methane humidity away from low latitudes [*Mitchell*, 2008] appears consistent with the idea that the preponderance of dunes within 30° of the equator may be due to those regions being effectively dried. As for winds, Cassini is not well-equipped to measure tropospheric winds on Titan directly (with the exception of the Huygens probe descent in January 2005) and because Titan has very few discrete clouds, there are few tracers to permit low-altitude wind measurements by feature-tracking in the near-infrared. Thus, the orientation of aeolian features on the surface yields one of the principal present constraints on knowledge of Titan's near-surface winds.

[4] Experiments with global circulation models [e.g., *Tokano*, 2008] suggest that the near-surface low-latitude winds should have zonal components that are predominantly retrograde (east-west), and meridional components that are generally greater than or equal to the zonal components. The meridional wind components appear to switch sign with the changing seasons, a finding that is qualitatively consistent with the observed duneforms (since bimodal winds separated by ~120° produce longitudinal dunes). However, the dune morphologies also indicate that the zonal components of the dune-forming winds were and/or are west-east, which is contrary to what current atmospheric models suggest. The cause of the discrepancy is not known, and may relate to effects of surface topography. Resolving the factors driving Titan's near-surface winds is important not only for understanding Titan's meteorology, but also for facilitating future missions, since leading concepts for future missions to Titan include wind-blown balloons [*Lorenz*, 2008].

2. Mapping

[5] We measured all discernable dunes in the Radar SAR swaths obtained during the Cassini Prime Mission, in total 16,355 measurements. Dunes were measured in the flyby swaths T3, T8, T13, T16, T17, T19, T21, T23, T25, T28, T29, T41, T43, and T44. Other SAR observations (TA, T7, T18, T30, T36 and T39, generally at high latitudes) showed no observable dunes. We used the 'measure tool' in the USGS image processing program ISIS2 (Imaging Software for Imagers and Spectrometers-2), optimized for Cassini data processing and analysis, to determine the start and end coordinates of dune segments (we did not correct for Titan's 0.3° obliquity and nonsynchronous spin, which are too small

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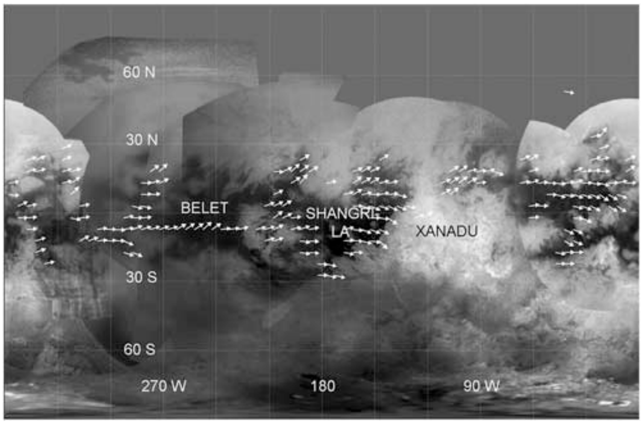

Figure 1. Radar-measured dune orientation vectors (5° bins), overlain on a near-infrared basemap derived from Cassini ISS (Imaging Science Subsystem) images (www.ciclops.org).

to affect our results here). Titan's dunes are typically radar dark compared to the interdune materials [*Lorenz et al.*, 2006; *Radebaugh et al.*, 2009] so in most locations it is easy to discern where the dune start and end points are located. However, the dunes often change direction over large distances (>50 km): dunes that form Y-shaped branches or changed direction significantly along their length were measured as separate line segments. The actual number of dunes is less than 16,355. However, even in terrestrial dune classifications, scientists are not in agreement over what defines a single dune, as the classification depends on the study at hand. For our purposes, each measured dune has a unique orientation, likely correlated with the vector sum of time-averaged, particle-carrying winds in that location [e.g., *Fryberger and Dean*, 1979; *Lancaster*, 1995].

[6] An isolated image of an individual duneform can have a 180 degree ambiguity to the corresponding wind direction, but we carefully studied morphological aspects of these dunes, their collective arrangement and interaction with surrounding terrains to determine that the sand transport is indicated in all cases from the west to the east. For example, dunes stop or divert around the upwind margin of topographic obstacles, then resume their course some distance downwind of the obstacle [*Radebaugh et al.*, 2009]. Radar-dark streaks form behind obstacles, likely due to particle deposition from decreased wind velocity. Finally, wind streaks visible in near-infrared observations [*Porco et al.*, 2005] also correlate with an eastward particle flow.

3. Results and Interpretation

[7] Figure 1 shows a global summary map of our measurements (we determine an average azimuth for the dune segments in 5 × 5 degree latitude-longitude boxes; for the convenience of other workers this dataset is available at http://www.lpl.arizona.edu/~rlorenz/dunes_t44_5.txt.

[8] Figure 2 shows that while indeed the observed coverage by dunes is influenced by the distribution of SAR data (e.g., the sharp peak at 10°S corresponding to the T8 flyby over Belet) it is clear that there is ample radar coverage at all latitudes to robustly confirm our earlier

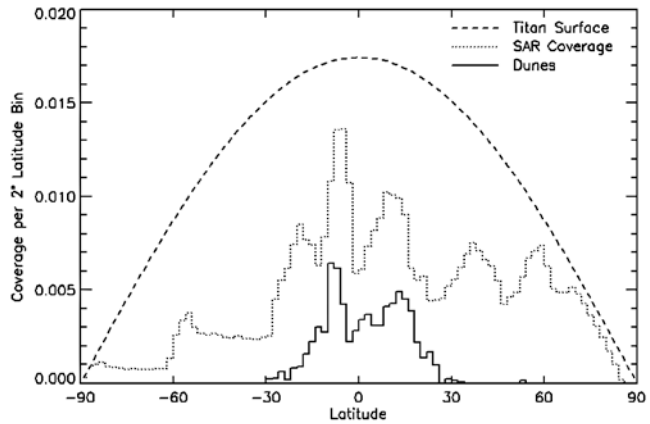

Figure 2. The latitude distribution of SAR observations through T44 and dune coverage. Note that the chart slightly overestimates dune coverage and observation area, in that a single 2 × 2 box is counted as 'dune-covered' or observed even if it has only a single dune (or observed pixel) in it. However, it is clear that the apparent confinement of dunes to ±30° latitude is real and is not due to observational bias.

suspicion [*Radebaugh et al.*, 2008] that dunes are essentially confined to ±30° latitude. Furthermore, the ~35% coverage of Titan's low latitudes (±30°) by SAR observations indeed indicates that dunes may cover approximately 20% of Titan's total surface area [e.g., *Lorenz et al.*, 2008]: our measurements to date directly show dunes on ~8% of the surface.

[9] Figure 3 shows the variation of dune azimuth with longitude: it might be expected since tidal accelerations are symmetric about the subsaturn point that if tidal effects in the atmosphere caused dune-forming winds that there might be a wavenumber-1 or wavenumber-2 pattern, yet none is obvious. Figure 4 shows the corresponding pattern with latitude – there is a weak correlation, with those dunes furthest from the equator deviating furthest from due eastwards, with dunes heading northwards in the northern

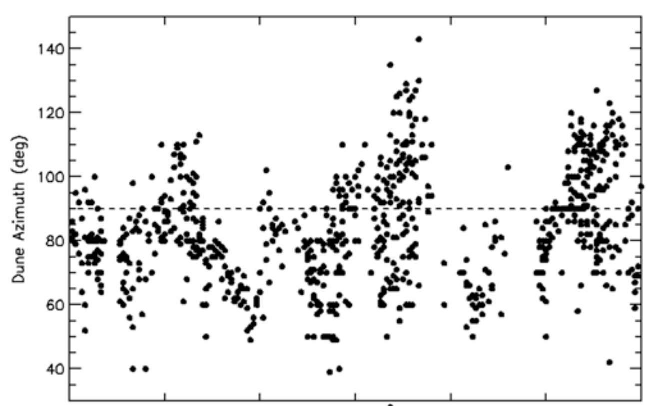

Figure 3. The azimuth of the dunes as a function of longitude. While there is evident local coherence in some regions, there is not an obvious periodic arrangement in either the mean or the scatter. The relative paucity of datapoints 70–140°W corresponds to Xanadu.

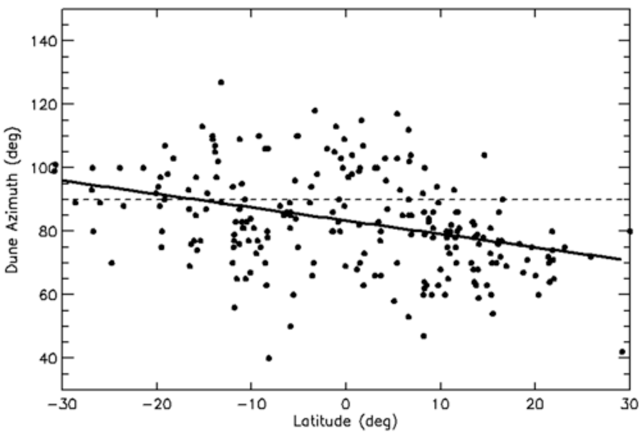

Figure 4. Correlation of dune azimuth with latitude. There is a tendency (correlation coefficient $R^2 = 0.13$), for dunes to be oriented northeastwards (Azimuth < 90°) in the northern hemisphere and southeastwards (Azimuth > 90°) in the south, although the data there are more sparse. The best fit line is Azimuth = 83 − 0.42 × Latitude.

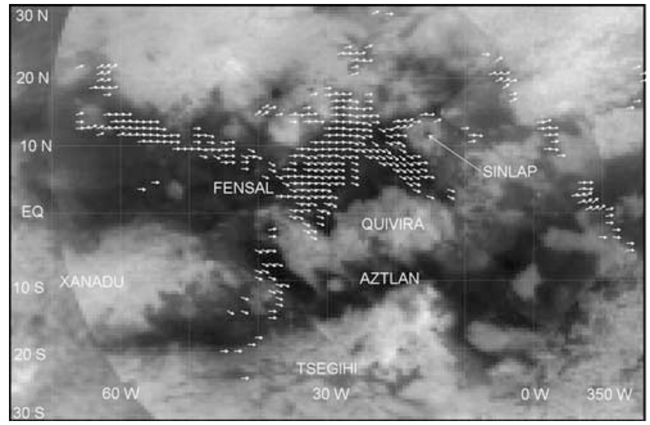

Figure 6. Zoom of the dune orientations (1° bins) in the Fensal-Aztlan region east of Xanadu. Note the divergence around the Sinlap impact crater's ejecta blanket (Bazaruto Facula) at 11°N, 16°W.

hemisphere and conversely in the south. Whether this is a manifestation of Coriolis effects remains to be confirmed with additional data or modeling. A counterexample to this pattern is the northeastern orientation of the discovery dunefields in Belet (T8, 10°S [*Lorenz et al.*, 2006])—it is possible that this may be a 'local' albedo or thermal inertia effect as we discuss later.

[10] Figures 5 and 6show the dune pattern at smaller scales (1°). The collimation of dunes between bright regions, and their diversion around them, is evident, notably around the Sinlap ejecta blanket in Figure 6 and, at a larger scale, the as yet unexplained divergence pattern of dunes around Xanadu.

4. Role of Albedo and Topography

[11] We noted previously [*Radebaugh et al.*, 2008, 2009] that dunes appear to deviate around obstacles at small (∼10 km) and large (∼1000 km) scales. In many cases, obstacles appear to be optically bright, and have been suspected of being topographically elevated since they stand distinctly from the dunes around them (see also *Radebaugh et al.* [2009] for Titan and terrestrial examples). However, it has so far been difficult to separate the influence of topography and albedo.

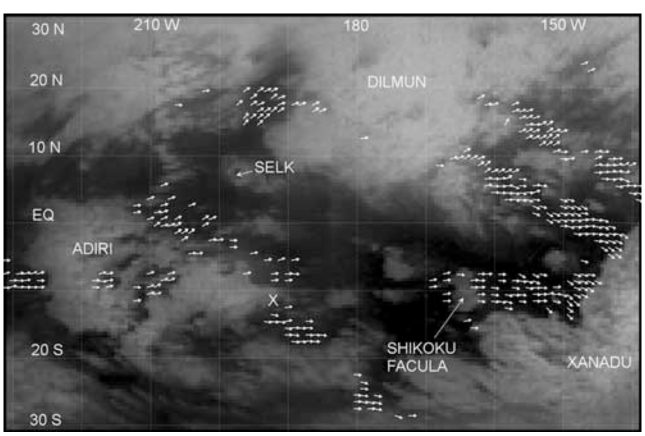

Figure 5. Zoom of the dune orientations (1° bins) in Shangri-La. The divergence at the north-east of this region is profound. The 'X' denotes the Huygens landing site, 192°W 10.3°S.

[12] There is presently very little data on Titan's topography – although as Cassini proceeds through its extended mission, altimetry and radar stereo coverage will build up. In the meantime, a new radar processing technique ('SARtopo' (B. W. Stiles et al., Determining Titan surface topography from Cassini SAR data, submitted to *Icarus*, 2009)) allows some terrain height information to be recovered over parts of many SAR image swaths, albeit only with a precision of 50–100 m (recall that radarclinometry of dunes in compositionally-uniform sand seas suggests that the largest dunes, 1–2 km wide, may be of the order of 100–150 m tall [*Lorenz et al.*, 2006]). A preliminary examination of the SARtopo data reveals a few instances where heights of dune obstacles can be determined.

[13] In cases where an obstacle is steep (e.g., the ejecta blanket of the impact crater Ksa—a 200 m rise over around 10 km; isolated hills observed on T17—300 m over ∼10 km and the rim of the Menrva impact structure, 200 m over 40 km) the dunes appear to stop abruptly, often merging into an irregular dark area perhaps of unsculpted sands. These obstacles correspond to slopes of the order of 1:50 to 1:20. On the other hand, larger and shallower obstacles (e.g., the Belet obstacle [*Lorenz et al.*, 2006, Figure 3]; the Sinlap ejecta blanket, 200 m over 100 km; and a regional slope in Shangri-La observed in T13, 100 m over 50 km) tend to cause the (climbing) dunes to peter out individually and/or deviate around the obstacle. These correspond to slopes of the order 1:500 to 1:200. Similar relationships of dune interaction depending on obstacle slope have been seen in terrestrial and martian sand seas [*Cooke et al.*, 1993; *Bourke et al.*, 2004]. A wider dataset to be examined in future work should be fruitful in more robustly delineating these two slope regimes and the role of the transverse extent of the obstacle.

[14] The SARtopo dataset shows that the large leading-face bright area Xanadu is not, in fact, elevated above its surrounds (Stiles et al., submitted manuscript, 2009). *Tokano* [2008] experimented numerically with both elevated and depressed Xanadu model topography and found significant local effects but neither configuration gave an overall eastwards dune pattern. *Tokano* [2008] noted that topography was a stronger effect on wind directions than albedo. On the other hand, the northeast-trend, giving apparent convergence of winds towards the center of the Belet sand sea (see Figure 1), might be consistent with a 'sea-breeze' type circulation, where the center of the large dark region experiences a warm updraft during the day and thus convergent flow.

5. Conclusions

[15] We have mapped Titan's dunes as revealed by the nominal mission Cassini SAR dataset. We confirm that dunes are essentially confined to 30° latitude, and cover about 20% of the satellite's surface. The dunes form coherent patterns over scales of ~1000 km: while there appears to be a correlation of orientation with latitude (diverging from the equator, although convergence at the center of Belet may be an exception), there is no obvious systematic longitudinal pattern. Rather, dunefields appear collimated by bright and/or elevated areas: topographic features with heights (~100 m) comparable with the dunes themselves are able to divert (shallow slopes, <1/200) or block (steep slopes, >1/50) dunes. These results provide important constraints on models of Titan's winds.

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