Modeling and Observing the Role of Wind-Waves on Titan's Hydrocarbon Seas: Adding Anemometry to Cassini's Repertoire. A. G. Hayes[1], J. M. Soderblom[2], M. A. Donelan[3], and R. D. Lorenz[4], [1]Cornell University, Astronomy Department, 412 Space Science Building, Ithaca NY (hayes@astro.cornell.edu), [2]MIT, Department of Earth, Atmospheric, and Planetary Sciences, Cambridge MA, [3]University of Miami, RMAS/Department of Ocean Science, Miami FL, [4]JHU Applied Physics Laboratory, Laurel MD

Introduction: Oceanography is no longer just an Earth Science. Standing bodies of liquid that interact with both atmospheric and surface reservoirs also exist on Saturn's largest moon, Titan [1]. Recently, Cassini observations have found evidence consistent with wind-waves on the surface of Titan's liquid bodies [2,3]. On Earth, wind-wave observing radars are commonly used as anemometers to measure surface winds [4]. Similar to these weather satellites, Cassini data can be used to estimate the RMS height and/or slope of roughness on Titan's lakes and seas. When coupled to a wind-wave generation model, these measurements can be used to estimate the wind speed necessary to drive an observed wave field. We couple a wave generation model to Cassini observations of roughness on Titan's lakes / sea surfaces to constrain surface winds.

Wave Model: The University of Miami Wave Model (UMWM, [5]) is a spectral wave model that can calculate the wavenumber-directional spectrum on any lake or ocean basin given the wind speed and direction at each grid point. The model also calculates the tangential stress of the wind on the surface. UMWM has been adapted to include all waves (gravity, capillary-gravity, and capillary) and to be applicable to any gas-liquid interface with merely a change in the fluid parameters (densities, viscosities, surface tension) and gravity. This universal wave and stress model is called UNIWSM. UNIWSM has been validated using wave tank experiments that varied liquid properties (viscosity & density) and atmospheric pressure (down to 40 mbars for Mars) [6,7].

We have adapted UNIWSM to the Titan environment and used it to model waves generated on Titan's hydrocarbon lakes in response to variable wind speeds (Fig. 1). While multiple liquid compositions have been modeled, this abstract will focus on best-fit compositions recently published by [8,9]. The wind-wave models produced by UNIWSM provide the link between wind speed and the RMS height and slope of wave-roughened liquid hydrocarbon surfaces. UNIWSM provides the framework necessary to provide Cassini with an anemometer capbility.

Measuring Surface Roughness: Cassini has three ways to measure the RMS height and/or slope on liquid surfaces: *VIMS Specular Reflections, RADAR Altimetry, and RADAR Scatterometry*. Of these, the VIMS off-specular glints provide the most numerous observations that have been interpreted as wave activity [2, Table 1]. When VIMS observes a specular reflection of the Sun from a part of a lake surface that should not have a specular reflection if it were perfectly smooth, the increased intensity tells us the fraction of the surface that is oriented in a particular direction (incidence angle +/- the VIMS IFOV/2) relative to the surface normal [see 10]. This quantity is known as the specular area fraction (SAF) and, for given wind speed, direction and incidence angle, can be directly compared to the output of the UNIWSM-Titan model (Fig. 2) to constrain wind speeds on Titan.

Using Cassini as an Anemometer: Figure 2 shows an area of Kraken Mare where a transient event consistent with wind-waves was observed by both RADAR and VIMS in August 2014. The SAF required to produce the observed reflection by VIMS was $5x10^{-8}$ (red line in Fig. 3). Figure 3 shows the SAF outputs from UNIWSM for various wind speeds as a function of wind direction (azimuth). A family of wind speeds are consistent with the observations depending on the wind direction. Regardless, SAF varies logarithmically with wind speed making Cassini a potentially sensitive anemometer on Titan. Figure 4 shows the wind speeds necessary to match the SAF measurements for several specular glints observed over Punga Mare in July 2012 [see 2]. If we assume that a similar wind speed generated all of the observed glints, the variable viewing geometries present a way to break the azimuth ambiguity. The required wind speeds converge near 0 azimuth, suggesting that the wind direction was within 20° of the spacecraft trajectory.

Summary: We have adapted a proven wave generation model to the Titan environment that can be used for a variety of applications. The brightness of VIMS specular reflections have a strong logarithmic dependence on both wind speed and azimuth angle, potentially explaining why off-specular glints are only rarely observed. The Kraken Magic Island and VIMS specular glints observed ober Punga Mare are consistent with wind-waves driven by 0.4–1.0 m/s winds.

References: [1] Stofan et al. (2007) *Science* 445 [2] Barnes et al. (2014) *PS, 3* [3] Hofgartner. et al. (2014) *Nat Geo., 7* [4] Plant et al.. (2005) *J. Atm. Ocean Tech. 22* [5] Donelan et al. (2012) *JGR, 117* [6] Donelan and Plane (2009) *JGR, 114* [7] Banfield and Donelan (2015) *Icarus 250* [8] Mastrogiuseppe et al. (2016 *IEEE, 54* [9] Mitchell et al. (2015) *GRL,* 42 [10] Soderblom et al. (2012) *Icarus, 220*.

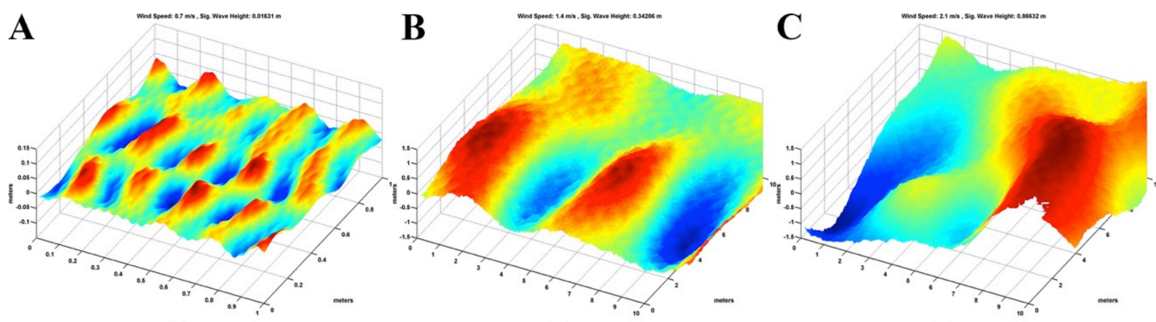

Figure 1: UNIWSM models for a 10 m deep patch of a methane lake under the influence of uniform 0.7 (A), 1.4 (B), and 2.1 m/s (C) winds for 17 min. Axes have a vertical exaggeration of 6.7. Note the order of magnitude change in the axes limits for panel A (0-1 /0-0.15 m) vs. B/C (0–10 / 0–1.5 m). Significant wave heights are 2 (A), 34 (B), and 86 cm (C).

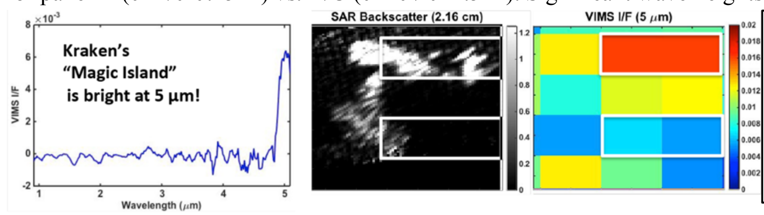

Figure 2: Cassini SAR (middle) and VIMS (right) observations observations of a transient feature in Kraken Mare acquired in August 2014. The leftmost panel shows the spectral signature of the transient as 5 µm bright.

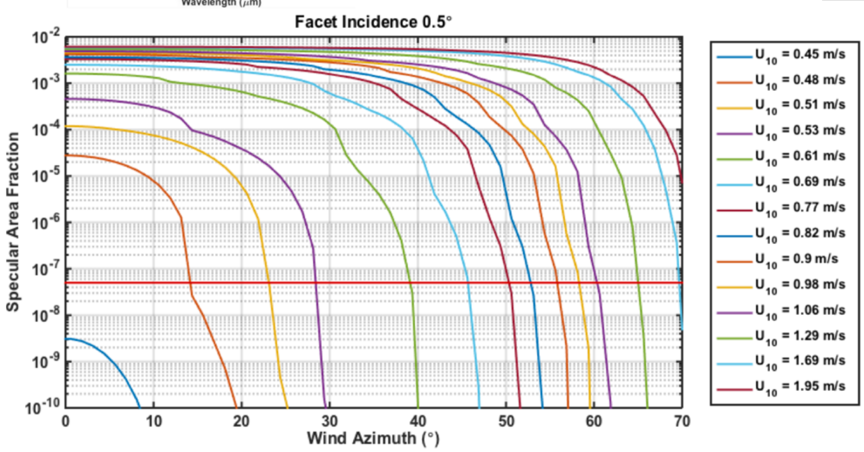

Figure 3: UNIWSM outputs of Specular Area Fraction (SAF) for a series of wind speeds as a function of wind azimuth. The red line represents the SAF consistent with the off-specular glint observed by VIMS over Kraken Marea in August 2014. Depending on the azimuth of the wind (relative to the spacecraft trajectory), a family of wind speeds are consistent with the observations. Modeling was conducted for a methane-dominatd lake.

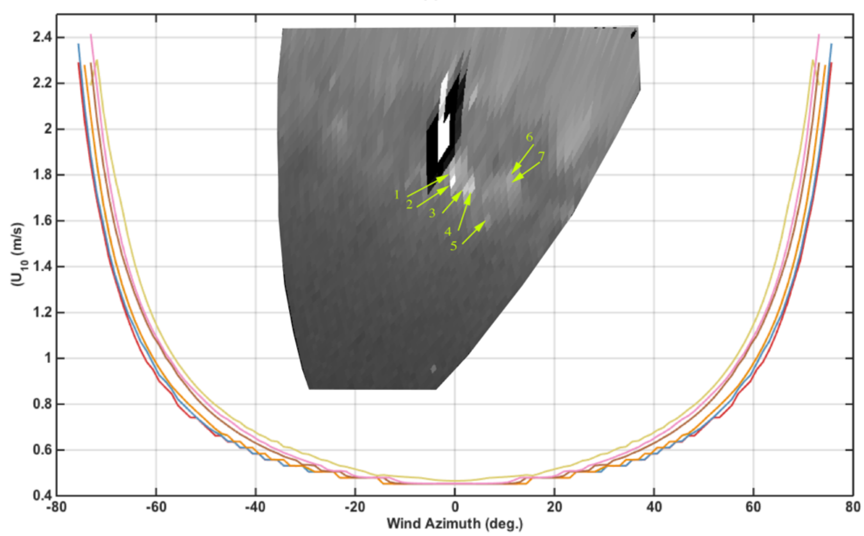

Figure 4: Wind Speed vs. Wind Azimuth for UNIWSM models consistent with the SAF observated over Punga Mare in July 2012 (center panel). These observations are discussed by [2]. Wind Speed estimates converge within 20° of 0 azimuth, suggesting that the wind direction was approximately in line with the spacecraft trajecory, assuming that the off-specular glints were driven by similar forcing. Multple observations with varying specular geometrty create a way to break the azimuth ambiguity. The logarithmic dependence of Wind Speed on SAF makes the diverage at large azimuth signifnicant.

Date	07/08/09	07/24/12	07/24/12	05/17/14	08/21/15	09/22/14	10/24/14	03/16/15	05/07/15
Target	Kraken	Punga	Kivu	Kraken	Kraken	Kraken	Kraken	Ligeia	Punga
Start	1627084350	1721788149	1721830711	1779839427	1787305664	1790059135	1791945922	1805212073	1809748858
End	1627165072	1721848119	1721854838	1779170296	1781353995	1790108386	1794380518	1805281254	1809770367
Num. Obs.	36	73	18	37	231	99	102	78	14

Table 1: List of VIMS observations with off-specular glints over liquid surfaces that have been interpreted as wave activity. Start and End numbers refer to PDS VIMS cube designations (e.g., T059-CM_1627084350_1.cub).