PHYSICAL OCEANOGRAPHY IN THE COASTAL ZONES OF TITAN'S PUNGA MARE.

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Introduction: Besides Earth, Titan is the only other planetary body to host large lakes and seas, albeit of liquid hydrocarbons. The oceanographic activity of the mediterranean seas of Kraken and Ligeia Mare (e.g. tidal currents and wind-waves) has been well explored by RADAR "magic islands" [1, 2] and near-infrared specular glint and sun glitter observations [3] from the *Cassini* mission. Instead, Punga Mare likely hosts a microtidal lake environment with only a single detection of probable capillary wind waves [4]. The lake environment should not limit the diversity of air-sea-land interactions. Punga Mare hosts a diversity of coastlines, similar to Ligeia Mare [5], that suggests a dynamic surface environment.

Specular glint observed on sea surfaces from orbit reveal many details of oceanographic activity on Earth [6] and Titan [3, 4] alike. The viewing geometry for specular glint is unique to every observation, which impacts surface brightness [6].

We present a high-sampling Cassini VIMS (Visual and Infrared Mapping Spectrometer) observation, CM_1805211625_1, of specular glint over eastern Punga Mare from the T110 flyby [7]. In Figure 1, the T110 observation shows a plethora of anomalous sea surface features, which suggests complex interactions with the hydrological cycle and dynamic surfaces around the shorelines of Punga Mare.

Specular Viewing Geometry: The T110 observation has a high phase angle of 126° that causes mirror-like reflections off of liquid surfaces, previously noted in radiative transfer models of Titan lakes [8]. Meanwhile, the roughness of the land exceeds the micron-scale VIMS wavelengths, leading to diffuse scattering from land surfaces.

In the unprojected T110 observation in Figure 1, several anomalous features appear as white, pink, or purple, either representing manifestations of sea surface activity or narrow hydrological features. The coastal locations of nearly all anomalous are consistent with active coastal zones, often common to Earth [6].

The specular deviation angle represents the distance between the specular point and a surface VIMS pixel [4]. *Cassini* recorded the T110 observation at a close-in spacecraft distance of 5,000 km in a hyperbolic orbital trajectory. As shown in Figure 2A, the specular point ends up travelling 323 km over the T110 observation time. As a result, the specular deviation angle surface distribution is oblique in the T110 observation, which is typically radial in most specular observations of Titan. Thus, the interpretation of the specular nature of each anomalous feature becomes complicated.

There are typically two zones in a specular glint observation: the specular and sun glitter zones [4, 6]. In the specular zone, smooth and rough sea surfaces appear brighter and dark than the background sea surface respectively. The opposite holds true for the sun glitter zone. However, VIMS is only sensitive to features brighter than the dark background sea surface due to the low NIR reflectance of liquid hydrocarbons [9]. The transition angle of the specular and sun glitter zones is important to determine the roughness of the anomalous features. We assume the zone transition occurs at 2.25°, based on prior interpretations of similar specular VIMS observations [3].

Discussion: We reference the right image of Figure 1 for this section. We observe variegated brightness in the sea surface of eastern Fundy Sinus in the specular zone, indicating rough and smooth seas. Winds cause roughened seas on open lake surfaces. The brightened purple feature occurs near Ipyr Labyrthinus, a plateau terrain known for deeply-carved channels on Titan [10]. We attribute the purple color to an enhanced brightness in the transparent 5 µm window only. We suggest weak 5 µm specular reflections derive from liquid-filled channels in Ipyr Labyrinthus. A line of brightened red pixels that aligns with a RADAR dark channel, known as Apanohuaya Flumen, also indicates liquid fill and the presence of a methane river.

Several features along the immediate the coastal zones The eastern Punga shoreline hosts a brightened band of white-pink pixels within the specular zone, indicating a smooth surface. While the immediate coasts may host solid floating debris, such as oil slicks on Earth, or wetted beaches on Titan, only smooth coastal seas are consistent with the likely kilometer size of the brightened coasts. Sun glitter, indicative of surface waves [3, 4], appears near Hawaiki Insulae and over 10 km off the southern Punga coast. The sun glitter near Hawaiki Insulae suggest a direct interplay between surface winds and possible elevated island topography. Finally, we note several bright pixels at the backside of Punga bays that likely correspond with river debouches sourced to nearby RADAR-bright mountains. Their occurrence in the sun glitter zone implies rough sea surfaces caused by a change in liquid flow regime at the debouches. Thus, possible sources for a change in liquid flow regime include river rapids or tidal races. Alternatively, experimental evidence suggests bubble outburst events may occur at river debouches [11] and can generate surface roughness.

Overall, the anomalous features in the T110 observation highlight the dynamic nature of the surface lake

lake environments and an active hydrological cycle on Titan.

References: [1] Hofgartner et al. 2014. [2] Hofgartner et al. 2016. [3] Heslar et al. 2020. [4] Barnes et al. 2014. [5] Wasiak et al. 2013. [6] Strong & Ruff, 1970. [7] Heslar & Barnes 2021, PSJ, submitted. [8] Vixie et al. 2015. [9] Soderblom et al. 2012. [10] Malaska et al. 2020. [11] Farnsworth et al. 2019

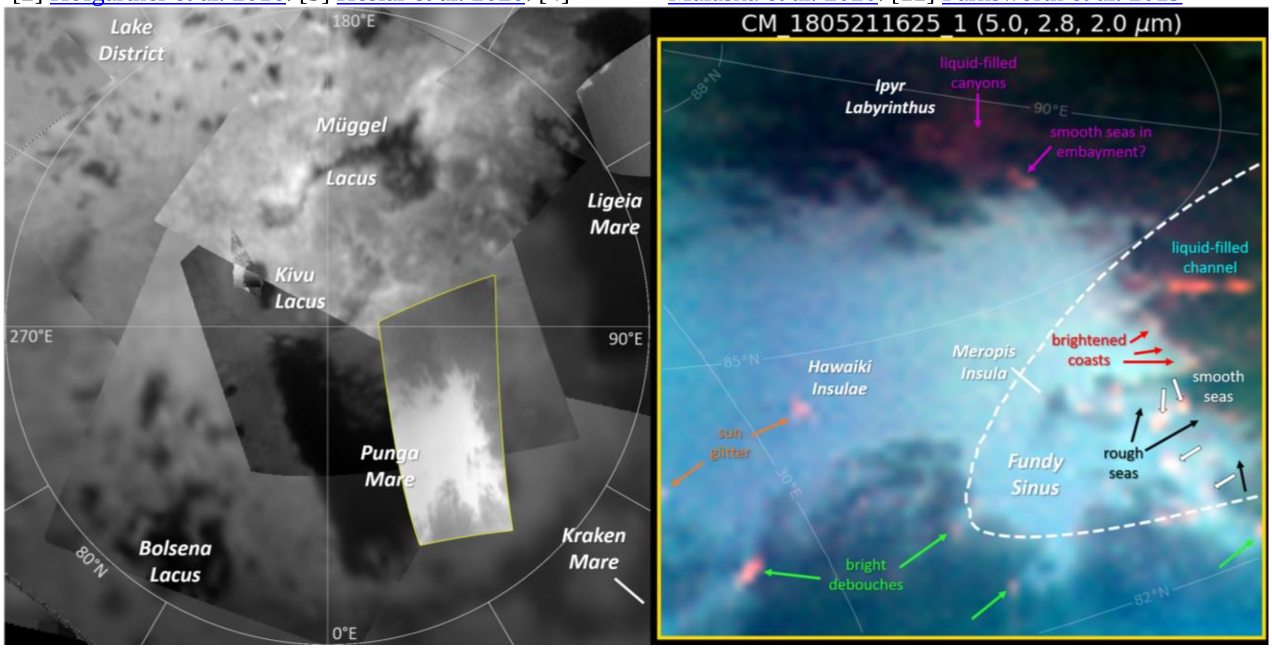

Figure 1: T110 observation of infrared specular glint on Punga Mare | *Left:* 2.03 μm polar stereographic mosaic of Titan's north polar region above 80°N from Cassini VIMS observations corrected for airmass and resolution. A yellow outline denotes the T110 VIMS observation, CM_1805211625_1. The high phase angle (126°) inverts the surface brightness such that liquid surfaces are brighter than the rougher land. *Right:* Unprojected color composite (RGB: 5.0, 2.8, 2.0 μm) of the same T110 VIMS observation with an superimposed geographic grid and IAU-approved feature names. Anomalous sea surface features of interest are pink and purple. The white dashed line indicates the transition between the specular and sun glitter zones. Note that this image is rotated by 180° from the original observation for a more reasonable north-to-south orientation.

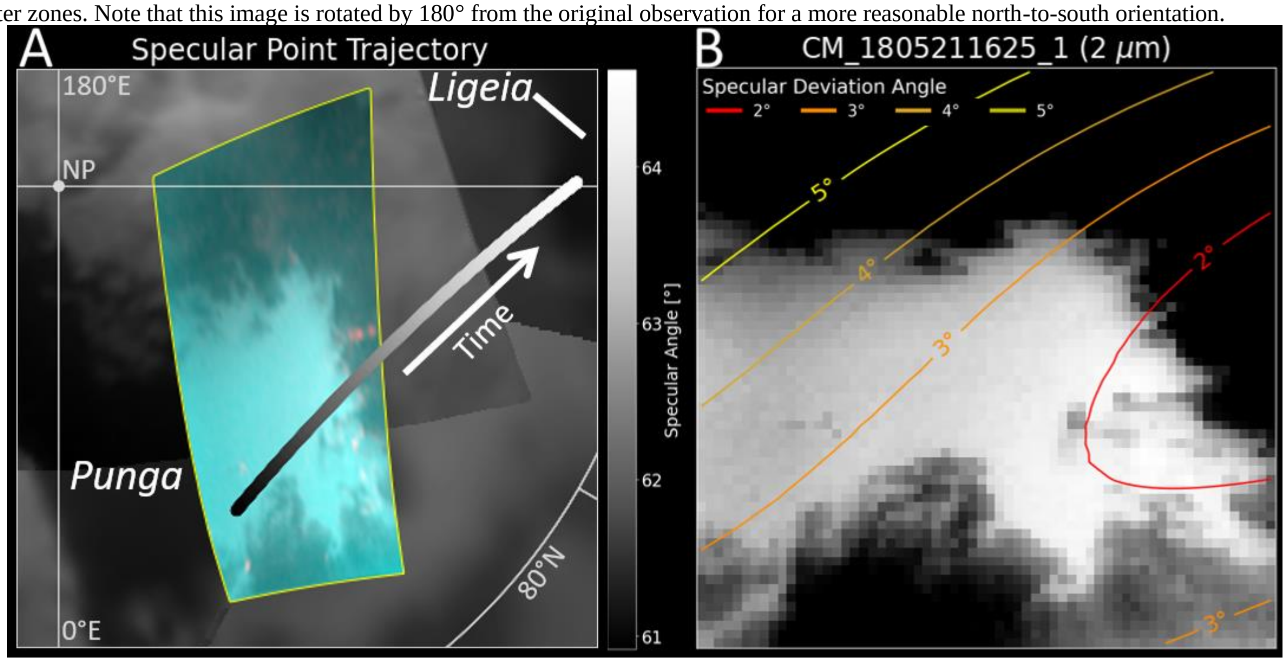

Figure 2: Details of the Specular Geometry | *A:* The path and specular angle of the solar specular point across Titan's north pole during the acquisition time of the T110 VIMS observation (5 minutes). The specular point traverses 323 km. A glare-like reflection of the sky appears on Punga Mare due to the large specular angle [2]. *B:* The moving specular point causes a non-radial distribution of the specular deviation angle (i.e. distance offset from the specular point) on the unprojected 2 μm T110 observation.