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# Cassini radar observation of Punga Mare and environs: Bathymetry and composition

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ABSTRACT

In January 2015 (fly-by T108), the Cassini radar observed Punga Mare, Titan's northernmost and third-largest sea, in altimetry mode during closest approach. The ground track intercepted a section of the mare and a system of channels and flooded areas connecting Punga to Kraken Mare. We use a processing technique, successfully adopted for Ligeia Mare and Ontario Lacus, for detecting echoes from the sea floor and constraining the depth and composition of these liquid bodies. We find that, along the radar transect, Punga Mare has a maximum measured depth of 110 m. The relative reduction in backscatter of the seafloor, as a function of increasing depth, suggests a liquid loss tangent of $3 \pm 1 \times 10^{-5}$. While this value is within the formal uncertainty of the loss tangent derived for Ligeia Mare, the best-fit solution is lower and is consistent with a nearly pure binary methane-nitrogen liquid with little to no ethane or higher order components. The indication of very low amounts of ethane toward the pole suggests that atmospheric processes are controlling the surface liquid composition of Titan's seas.


## 1. Introduction

Titan's surface has been widely mapped by the Cassini RADAR (2004–2017), a microwave remote sensing instrument able to penetrate the dense atmosphere of the moon at 2.17 cm wavelength. The Cassini radar was a multimode instrument capable to operate in active mode as a Synthetic Aperture Radar (SAR) for surface imaging, as a radar altimeter for topography measurements, as a scatterometer for surface composition and, in passive mode, as a radiometer for brightness temperature (Elachi et al., 2004). The instrument modes were activated sequentially during each fly-by to Titan, from an altitude of 100,000 km down to a 1,000 km at the closest approach, pointing the antenna in a convenient way to accomplish the targeted measurements. A detailed description of sequence planning and instrument performance is reported in West et al. (2009). A total number of 53 fly-bys dedicated to the radar observations, allowed Cassini to cover ~50% of Titan surface at <1 km resolution in SAR mode, as well as to acquire 40 topographic profiles in altimetry mode. This dataset enabled the identification and characterization of a series of geomorphologic features, including hundred meters high dunes (Mastrogiuseppe et al., 2014b), fluvial network of channels and canyons (Poggiali et al., 2016), mountains (Radebaugh et al., 2007; Mitri et al., 2010), craters (Wood et al., 2010), possible cryovolcanic features (Lopes et al., 2013) and large deposits of liquid hydrocarbons in lakes and seas. A detailed description and mapping of the Titan's polar terrains is reported in Birch et al. (2017).

The presence of standing hydrocarbons liquid bodies on Titan was revealed by Cassini on July 22nd, 2006, during the fly-by T16, when the radar mapped a collection of 10–100 km diameter lakes present in the Northern hemisphere (Stofan et al., 2007). Later observations revealed the existence of three northern seas, or maria: Kraken Mare, Ligeia Mare and Punga Mare (Hayes et al., 2008).

The altimetric observation acquired in May 2013 (flyby T91) over Ligeia Mare demonstrated that the Cassini RADAR can also operate as a sounder, capable of probing Titan's seas down to ~200 m, depending mainly on liquid composition (Mastrogiuseppe et al., 2014a). This was possible because of the very low microwave absorptivity of liquid hydrocarbon (methane and ethane), which has a microwave loss tangent (defined as the ratio between the imaginary and real components of the dielectric constant) that is approximately five orders of magnitude lower than seawater. This successful experiment suggested a re-design of the final targeted

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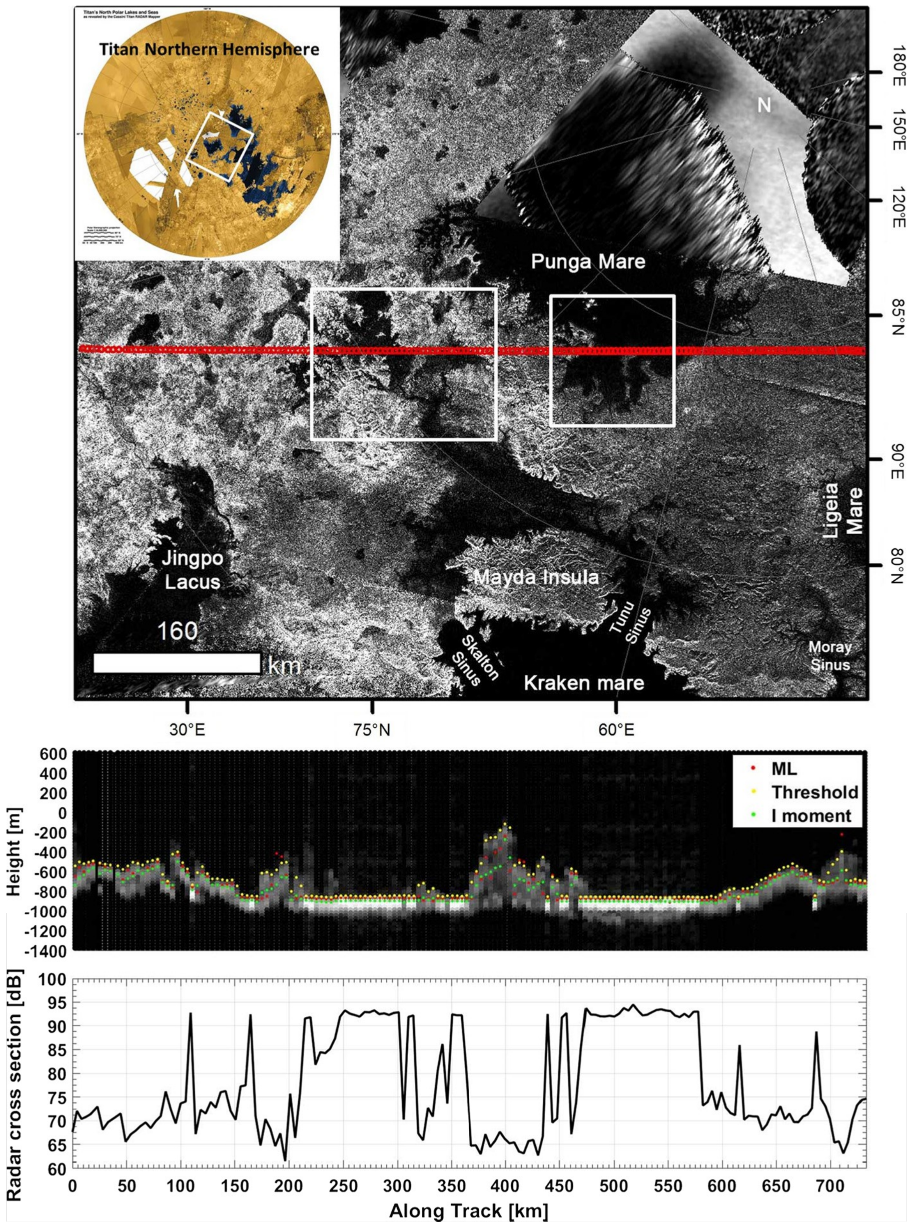


**Fig. 1.** (Upper panel) SAR mosaic and relative outbound altimetric 700-km-long track of flyby T108 with red circles indicating half power footprints and, in white, the two selected regions shown in Fig. 2. (Middle panel) Radargram and relative altimetry obtained using different tracking methods. (Lower panel) Radar cross section obtained from altimetry. Note that the abrupt changes to very high values of radar cross section indicate the presence of exposed liquid intercepted by the radar. (For interpretation of the colors in the figure(s), the reader is referred to the web version of this article.)

observations of Titan aimed at acquiring similar altimetry datasets over Titan's other seas in order to investigate their depth and composition. Herein, we discuss the January 11th, 2015 observation (flyby T108) of the Cassini RADAR, that acquired data over a ∼100 km long transect through Punga Mare and a portion of the flooded terrain connecting Punga and Kraken Mare during the spacecraft's closest approach to Titan, with a favorable geometry for sounding (Fig. 1 and Supplementary material).

Punga Mare has been repeatedly observed by the Cassini RADAR in its high-resolution SAR mode, notably in October 2006 (T19), April 2007 (T29) and December 2009 (T64). It is the third largest ($6.1 \times 104$ km$^2$, Hayes, 2016) and most poleward sea on Titan (85°N, 342°W). At the time of the T108 altimetry observation, Punga Mare's surface was very smooth at the Cassini radar wavelength ($\lambda = 2.17$ cm). Investigation of the surface roughness from T108 altimetry resulted in an estimated effective $\sigma_h$ (standard deviation of the surface height) ranging between 2.3 and 2.5 mm (Grima et al., 2017), consistent with a lack of wind-waves (Hayes et al., 2013). In July 2012 (T85), the Cassini Visual Infrared Mapping Spectrometer (VIMS) observed offset sun glints that were characterized as isolated patches of increased roughness consistent with wind-waves (Barnes et al., 2014). In order to produce the observed glint magnitudes, the wind-waves would have required "Significant Wave Heights" ($\mathrm{SWH} = 4\sigma_h$) of $2^{+2}_{-1}$ cm (Barnes et al., 2014), consistent with wave fields generated by light winds of 0.4–0.7 m/s near the threshold for wave generation (Hayes et al., 2013).

In this paper, we adopt the dedicated radar processing technique described in Mastrogiuseppe et al. (2016) to quantitatively investigate the seafloor topography and composition of the liquid basins observed during fly-by T108. This technique has been successfully used to characterize the depth and composition of Ligeia Mare (Mastrogiuseppe et al., 2014a, 2016) and Ontario Lacus (Mastrogiuseppe et al., 2018) as reported in Table 1. A similar anal-

**Table 1**
Depth and composition values from Cassini radar assuming a ternary methane–ethane–nitrogen composition.

| Mare | Best fit / Limits ($1\sigma$) | | |
|---|---|---|---|
| | Methane [%]<br>Mean value / (1-sigma) | Nitrogen [%]<br>Mean value / (1-sigma) | Ethane [%]<br>Mean value / (1-sigma) |
| Ligeia | 71 / (63-78) | 17 / (14-20) | 12 / (2-22) |
| Punga and Baffin Sinus | 80 / (74-80) | 20 / (18-20) | 0 / (0-8) |
| Ontario Lacus | 51 / (21-74) | 11 / (05-18) | 38 / (08-74) |

ysis, which adopts a waveform approach, has also been used to derive Titan's solid body topography (Mastrogiuseppe et al., 2014b).

## 2. T108 data analysis and seafloor detection

In altimetry mode, the Cassini RADAR collected data by pointing the antenna boresight toward the center of mass of the moon, transmitting/receiving bursts of chirped signals with a pulse repetition frequency (PRF) of 5 kHz and a bandwidth of 4.25 MHz allowing a range resolution equal to 35 m in vacuum. When the radar altimeter is used as a sounder (bathymetric investigation), the range resolution is degraded to 50–60 m due to the application of custom taper functions for suppressing side lobes associated to the strong sea-surface reflection (see Supplementary material). In this work we adopt super-resolution techniques (Cuomo, 1992) to extend the standard Cassini radar bandwidth by a factor of three, allowing roughly 20 m resolution for shallow depth investigations of Titan seas and lakes.

The dedicated outbound radar altimetry observation conducted during the T108 fly-by, enabled collection of data along a 700 km ground track with spacecraft altitudes ranging from 1000 km to 1200 km above Titan's north polar terrain (Fig. 1 and Supplementary material).

During this fly-by, the antenna was pointed close to the nadir direction ($\theta < 0.035$ deg, see Supplementary Fig. S1) and its footprint intercepted the southern eastern part of Punga Mare, as well as a flooded area that connects Punga with Kraken Mare. Over the predominantly land surface of the swath, nadir glints from small patches of liquids such as small lakes and rivers, similar to those detected during the fly-by T91 (Poggiali et al., 2016), were also observed. The processing results are reported in Fig. 1, where the middle panel shows the radargram and relative altimetry of the observation and the upper panel the SAR mosaic of the region of interest. The altimetric profile obtained using conventional processing (Alberti et al., 2009), shows the presence of a complex topography where flat regions representing liquid bodies are followed by hilly regions rising hundreds of meters above the liquid surface along a slope of a few degrees. Two major liquid bodies are observed during the flyby. First, located from ~200 to 350 km along track (Fig. 1), is an estuary connected to northern Kraken Mare, hereafter simply referred to as Baffin Sinus. The second, from 470 to 570 km, is the southern part of Punga Mare. The smooth surface of both liquid bodies resulted in a very strong specular return (Fig. 1, bottom panel), permitting very precise measurements (~30–50 cm) of the distance between the spacecraft and liquid surfaces. Across the ~350 km of track over Punga Mare and Baffin Sinus, the liquid surfaces are observed to smoothly change by ~11 m (Hayes et al., 2017), consistent with estimate of Titan's geoid variability over the same track by Iess et al. (2012). Along with elevation measurements of Ligeia Mare and Kraken Mare, Hayes et al. (2017) used this observation to argue that Titan's Maria are connected and share a common equipotential surface (like Earth's oceans).

The results of the standard altimetric processing of the T108 radar product is shown in Supplementary Fig. S2. Radargrams show signals reflected by the smooth surface of the liquid in addition to side lobes resulting from the processing (Supplementary Fig. S2, upper panels). Reprocessing data using a custom taper function (Blackman window, Blackman and Tukey, 1959) resulted in a mitigation of side lobes (Supplementary Fig. S2, middle panels). Subsequently, we apply super-resolution technique to enhance range resolution and improve the detection of shallow (<35 m deep) subsurface echoes (see Fig. 2, bottom panel). The same technique was implemented on the T91 radar data acquired over Ligeia Mare for discriminating subsurface echoes at the shoreline of the sea (Mastrogiuseppe et al., 2014a). The result of the processing is shown in Fig. 2 (central panel) and the radargrams show the presence of echoes reflected from the seafloor of Punga Mare and nearby liquid bodies.

In Fig. 2, the lower-right panel shows a detection of liquid over the relatively small Dingle Sinus, a flooded area which connects Punga and Kraken maria. The resulting waveform shows a specular reflection from the surface followed by a weaker reflection from the subsurface. Although we applied super-resolution algorithms, the subsurface return cannot be separated from the echoes at the surface, suggesting that the depth is shallower than the limit of detection (15–20 m) after super-resolution processing.

## 3. Bathymetry and composition of Punga Mare and Baffin Sinus

We investigate the depth and composition of Punga Mare using the Monte Carlo approach described in Mastrogiuseppe et al. (2016). This technique, already applied to the data acquired during T91 (Mastrogiuseppe et al., 2016) and T49 flybys (Mastrogiuseppe et al., 2018), estimates the most probable values and relative uncertainties for the three parameters used for deriving the loss tangent of the liquid and bathymetry: surface to subsurface relative peak power ($P_s/P_{ss}$), two-way travel time of the echo ($\Delta\tau$) and subsurface roughness ($\sigma_h$).

Subsequently, the estimated values ($P_s/P_{ss}$ and $\Delta\tau$) are used along with a parametric model for determining the specific signal attenuation $K$ of the liquid, written as logarithmic loss per travel time as described in Mastrogiuseppe et al. (2016).

A linear regression is applied to a subset of data, including only selected bursts where the −3 dB footprint intercepted exclusively the liquid, thus not selecting the bursts where the footprints overlap the coastlines. The selection resulted in 21 footprints and in a mean value of specific attenuation $K = 13^{+5}_{-6}$ dB/μs (1-sigma uncertainty) for Punga Mare, and 17 footprints with a mean value of $K = 10^{+6}_{-8}$ dB/μs for Baffin Sinus (Supplementary Fig. S3 and Table S1).

The estimated attenuation when converted into loss tangent gives a value of $\tan\delta = 3^{+1}_{-1} \times 10^{-5}$ (1-sigma uncertainty) for Punga and $3^{+1}_{-2} \times 10^{-5}$ for Baffin Sinus.

Assuming that the liquid is composed of a ternary mixture of methane, ethane, and nitrogen, we determined the composition of the Punga Mare and Baffin Sinus using the component dielectric properties measured by Mitchell et al. (2015) and the same assumptions adopted as for Ligeia Mare and Ontario Lacus (Mastrogiuseppe et al., 2016, 2018):

1) Ethane and methane are the most abundant materials on Titan that have loss tangents low enough to match our inferred value. They are liquid under Titan conditions. (No solid compounds have the requisite low loss tangent.)

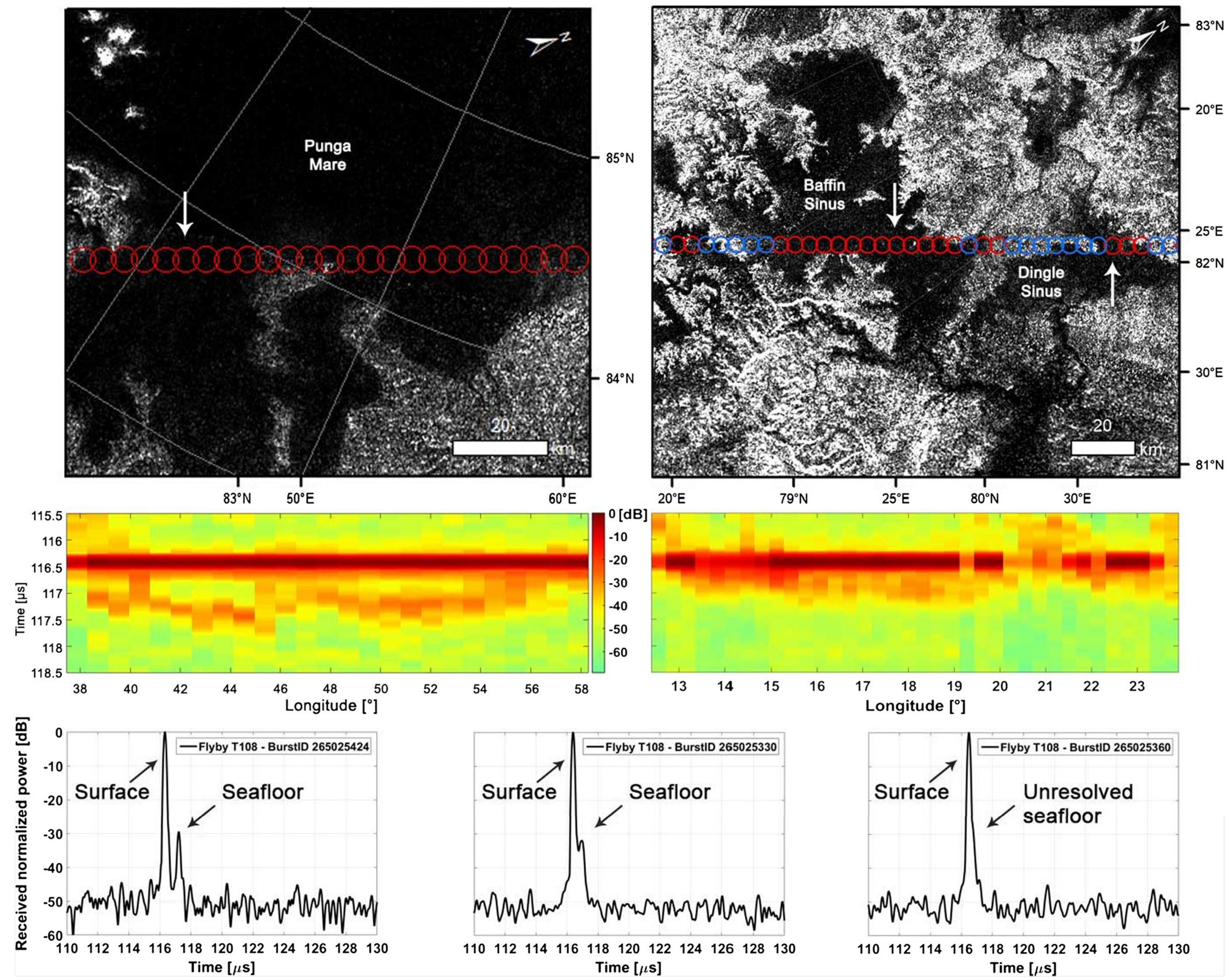


**Fig. 2.** (Upper panels) SAR mosaic showing the location of the −3 dB beam-limited altimeter footprints over liquid (red circles) and solid surfaces (blue circles). Note that the footprints barely overlap. (Middle panels) Super-resolved radargram: Punga mare (left) and nearby liquid bodies (right). (Bottom panels) Three waveforms received over Punga Mare (left), Baffin Sinus (middle) and Dingle Sinus (right): locations of relative footprints are indicated by white arrows.

2) Nitrogen is a dissolved component whose mole fraction in the liquid is determined by the partial pressure (1.5 bars) of nitrogen in contact with the open seas, the solubility of nitrogen measured in pure ethane and methane (Cheung and Wang, 1964), and in the binary ethane–methane system (Malaska et al., 2017).

3) The 2.18 cm wavelength microwave absorption coefficient of the mixture is a combination of its individual components as determined by Mitchell et al. (2015) using the Lorentz–Lorenz mixing rule, for nitrogen mixing ratios in methane–ethane determined by Malaska et al. (2017) assuming a temperature of 91 K. For a temperature of 95 K the ethane mole fraction will increase slightly and the nitrogen decrease.

We note that the best-fit loss tangent for Punga Mare and Baffin Sinus is close to the $3.3 \times 10^{-5}$, value given in Mitchell et al. (2015) for a purely binary mixture of methane and molecular nitrogen, with the latter's mixing ratio determined by its solubility in liquid methane under the 1.4 bar atmospheric pressure (see Malaska et al., 2017). Our best-fit composition for the observed loss tangent is therefore a binary mixture of 80% $CH_4$ and 20% $N_2$, with only trace amounts of ethane and/or high-order components which would cause higher absorption. We note that the uncertainties of the loss tangents of Ligeia Mare (Mastrogiuseppe et al., 2016), Punga Mare, and the Kraken Mare's Baffin Sinus significantly overlap.

Considering the estimated composition of Punga Mare and using the Lorentz Lorenz formula (Born and Wolf, 1999), we derived the real part of the dielectric component of the mixture as $1.67^{+0.05}_{-0.05}$. This value is consistent with the low emissivity measured by the radiometry (Le Gall et al., 2016; Janssen et al., 2016) and is used as input to generate the bathymetry of the mare and constrain the seafloor roughness.

Results of the Monte Carlo estimates and relative uncertainties are reported in Fig. 3, which shows that the maximum depth for Punga Mare measured along the track is about 110 m. The derived along-track bathymetry is consistent with the observational evidence obtained from SAR images of both Punga Mare and Baffin Sinus (Figs. 1 and 2). The seafloor of Punga Mare shows a 50 meter elevation rise due to the presence of the central island visible from SAR images (see Fig. 2, upper-left panel). Moreover, there is an overall agreement between the derived seafloor profile and the bathymetry that would be qualitatively inferred from the morphology (e.g. shape of coastal features, presence of bays, distance from shorelines) of the mare and the brightness of the SAR images, if interpreted as a proxy for the seafloor depth. Based on the