The Bathymetry and Composition of Titan's Lakes and Seas

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THE BATHYMETRY AND COMPOSITION OF TITAN'S LAKES AND SEAS

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Introduction: Despite pre-launch predictions that hydrocarbon liquids would be transparent to Cassini's 13.8 GHz radar [1] and that the radar's altimetry mode might be used as a sounder to probe Titan's liquids [2], experiments using liquefied natural gas by Paillou et al. [3] suggested that penetration would be significantly shallower than the altimeter's 35 m range resolution. Nevertheless, Mastrogiuseppe et al. [4] successfully detected subsurface reflections in altimetry echoes acquired over Ligeia Mare in May 2013 (Figure 1). Coherent processing of these echoes revealed the bottom reflection and allowed construction of a bathymetry profile as well as an estimation of the liquid loss tangent from the relative variation in subsurface power. Subsequent altimetry observations of Kraken and Punga Maria obtained in August 2014 and January 2015, respectively, also showed detectable subsurface echoes. After applying these new techniques, subsurface echoes were also observed in altimetry data acquired over Ontario Lacus in 2008. In this proceeding, we will report on the latest results from the analyses of these altimetry passes.

Bathymetry: The relative variations in received subsurface power as a function of depth provided an estimate for the Ligeia Mare's loss tangent $tan\Delta=\varepsilon_i/\varepsilon_r =4.4\pm0.9\text{x}10^{-5}$ [5]. Initial analysis of Kraken and Punga Maria suggest liquid absorptivities that are similar to Ligeia Mare. Portions of Kraken Mare were too deep (or too absorptive) to detect the seafloor. Recent laboratory experiments reported by Mitchell et al. [6] confirmed the low absorption of methane and ethane.

Mastrogiuseppe et al. [7] applied similar processing to low altitude (~1800 km) altimetry acquired over Ontario Lacus in December 2008 and, despite significant saturation in many echoes, detected subsurface reflections and retrieved depths of up to 50 m across the observed transect. These results are consistent with the near-shore depths reported in Hayes et al [8], which extended shoreline slopes into the lake. The best-fit loss tangent for Ontario is $tan\Delta=7.0\pm1.0\text{x}10^{-5}$. This is ~59% greater than the loss tangent reported for Ligeia Mare but an order of magnitude less than the absorptivity suggested by Hayes et al. [8] from analysis of near-shore off-axis SAR. The discrepancy could be explained by an increase in microwave absorptivity near the shore resulting from an increased concentration of solutes or suspended particles as compared to the center of the lake. Such a scenario would be consistent with the observation that the near-shore ethane bands, unlike central Ontario Lacus, are not saturated [9]. In this case, photons would be scattered before traveling through a path length sufficient to saturate the ethane absorption.

Prior to the work of Mastrogiuseppe et al. [4], the unknown dielectric properties of both the liquid and the seabed limited the utility of SAR backscatter as a tool for estimating the of depth Titan's lakes and seas. With the bathymetry profile and liquid loss tangent of Ligeia Mare in hand, SAR data can be calibrated and used to generate bathymetric maps. Hayes et al. [10] derived an empirical backscatter function for the seabed using SAR backscatter in the altimetry footprints of Ligeia Mare. This empirical function was used to derive depths for all of the Mare observations that have SAR returns above the instrument noise floor, assuming uniform seabed reflectivity (Figure 2). A similar analysis was performed for Ontario Lacus, revealing that the lake reaches depths of up to 90 m. Lorenz et al. [11] calculated a liquid volume by assuming that seadepth was linearly proportional to the distance from the nearest shoreline, calibrated such that the maximum depth scaled linearly with the square root of Mare area. Combining results from both techniques yields a lower limit of ~70,000 km^3 for the total volume of Titan's lakes and seas. If this liquid were spread across the surface equally it would be equivalent to a global ocean depth of ~1 m. This is equivalent to 14 times the volume of Lake Michigan, 300 times the mass of Earth's proven natural gas reserves, and 35 times the mass of all terrestrial fossil fuel reserves (natural gas, crude oil, and coal). Unlike Earth, where the total water content in the atmosphere ($1.29\text{x}10^4$ km^3) is only a fraction of the surficial reservoir ($1.35\text{x}10^9$ km^3), the moisture content in Titan's atmosphere is approximately seven times larger than the volume found in its lakes and seas. Unless Titan had a significantly larger liquid reservoir as compared to atmospheric methane, or currently has a large subsurface reservoir hidden from remote sensing, climate feedback would be improbable since the detectable volume is unlikely to significantly impact the atmospheric composition.

Composition: Thermodynamic equilibrium models by Cordier et al. [12] predict ethane-rich lake compositions, while more recent work by Glein and Shock [13] and Tan et al. [14] predict methane-dominated compositions at Titan's polar latitudes. Luspay-Kuti et al. [15] attribute the differences between these models to the use of varying underlying theories relying on experimental data which may not be relevant in Titan conditions. The most recent experimental results reflect methane-dominated compositions. Using the laboratory measurements of Mitchell et al. [6] and assuming a methane-ethane-nitrogen composition, Mastrogiuseppe et al. [5] determined that the measured loss tangent of Ligeia Mare was consistent with ~69% CH_4, ~14% C_2H_6, and ~17% N_2, similar to the equilibrium compositions predicted by Glein and Shock [13] and Tan et al. [14]. Note that if Titan's lakes are near vapor equilibrium with the atmosphere, evaporation rates would be significantly reduced despite their methane-dominated compositions.

Assuming a similar ternary composition, the increased loss tangent at Ontario Lacus is consistent with ~47% CH_4, ~40% C_2H_6, and ~13% N_2 [7]. The higher loss tangent could result from an increased abundance of more involatile hydrocarbons and/or nitriles; these species could be concentrated as a consequence of orbitally-driven insolation cycles that may have slowly transported volatile components (methane/ethane) to the north over the past several tens of millennia [16].

Non-polar solutes such as acetylene (C_2H_2) and benzene (C_6H_6) may have low loss tangents similar to methane and ethane. Nitriles, like hydrogen cyanide (HCN) and acetonitrile (C_2H_3N), are likely quite absorptive and even minor concentrations may affect the loss tangent. Once the complex permittivities of potential hydrocarbon and nitrile solutes in Titan's lakes are measured in the lab, they can be used to place upper limits on the concentration of these species in Titan's liquids. The observed volume and composition of the seas do not accommodate the inventory of ethane and other species predicted by photochemical models. This suggests that the products of methane photolysis fall into a sink other than the lakes and seas, such as crustal sequestration of ethane in clathrate-hydrates [17]. Also of note is that while the transparency of Ligeia Mare allows SAR backscatter to penetrate through over 100 m of liquid, the backscatter from many of the smaller lakes are below the radar's noise floor [18]. This suggests that these smaller lakes are either extremely deep or, perhaps more likely, that they have a more absorptive composition than the seas. The latter hypothesis is consistent with dissolution-based formation scenarios for the smaller lake basins wherein liquids become saturated with soluble components from the regolith. Regardless, the lakes still cannot account for the missing ethane.

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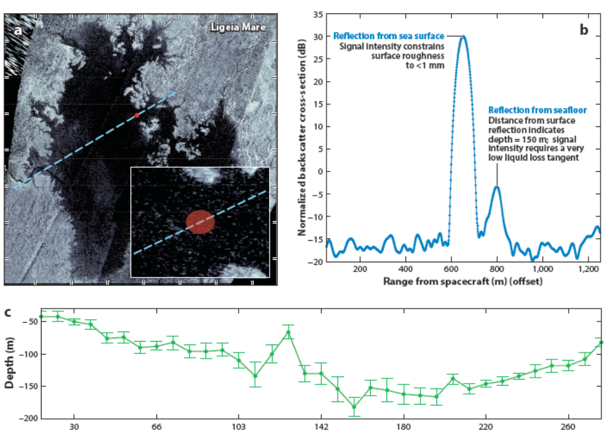

Figure 1: RADAR sounding measurements over Ligeia Mare. (*a*) A Synthetic Aperture Radar (SAR) mosaic of Ligeia Mare with the position of the May 2013 (flyby T91) altimetry track highlighted and the location of an example altimetry echo shown on the right. (*b*) An example of a double-peaked waveform observed over Ligeia, with returns from the sea surface and seabed labeled. (*c*) The along-track bathymetry derived by Mastrogiuseppe et al. [4,5].

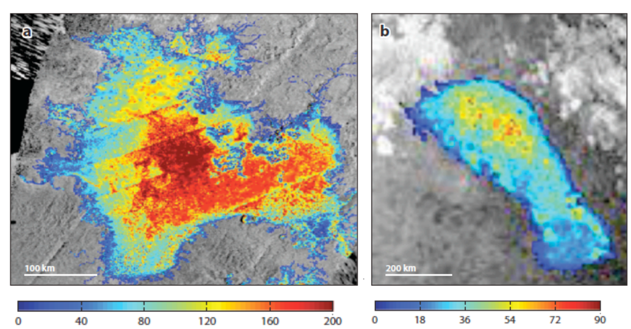

Figure 2: Synthetic Aperture Radar (SAR)-based bathymetric maps of (*a*) Ligeia Mare and (*b*) Ontario Lacus generated assuming a uniformly scattering seabed using the techniques and algorithms described by Hayes et al. [10]. Ligeia Mare has an estimated volume of 14,000 km^3, equivalent to 2.8 times the volume of Lake Michigan. Ontario Lacus has an estimated volume of 560 km^3, equivalent to 1/3 the volume of Earth's Lake Ontario.