The Distribution and Volume of Titan's Hydrocarbon Lakes and Seas.
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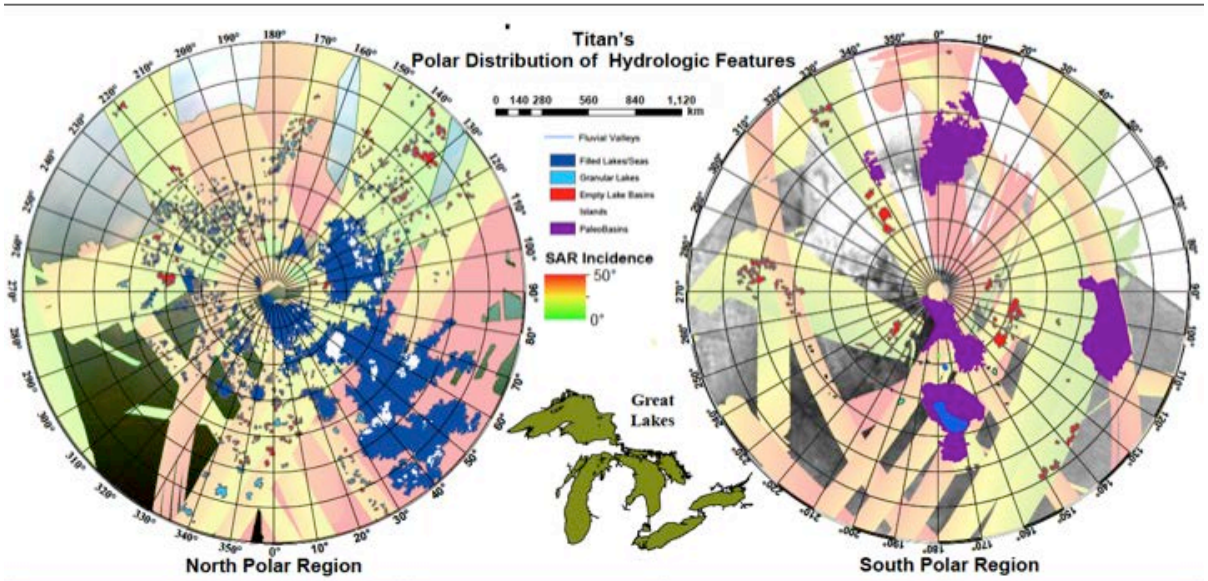
Abstract: We present a complete map of Titan's polar lacustrine features, at 1:100,000 scale, using a combinatio of images acquired using the RADAR, VIMS, and ISS instruments onboard the Cassini spacecraft. Synthetic Aperture Radar (SAR) images are used to define morphologic borders while infrared images from ISS and VIMS are used to determine state of liquid-fill. In addition, liquid volume estimates are derived from SAR observations using a two-layer model calibrated by recent time-of-flight bathymetry measurements of Ligeia Mare. Lakes and Seas cover ~1.1% of Titan's global surface area and contain ~70,000 km^3 of exposed liquid, comparable to ~15 times the volume of Earth's Lake Michigan.

Lake Distribution: Titan's polar terrain can be broadly described as consisting of smooth undulating plains, dissected uplands, and more heavily dissected labyrinthic morphologies. Inset into the undulating plains are broad and steep-sided depressions, each of which are found in varying states of liquid fill (dry, bottom wet, and filled). Titan's northern seas (Kraken, Ligeia, and Punga Maria) are examples of liquid-filled broad depressions while the smaller lakes (e.g., Cayuga Lacus) predominantly consist of liquid-filled steep-sided depressions [1,2]. Collectively, these features account for ~1.1% of Titan's globally observed surface area, while Kraken, Ligeia, and Punga Maria account for ~80% of all filled lake features by area. The vast majority of filled lakes exist in the Northern hemisphere, taking up 12% of the area poleward of 55° as opposed to 0.3% in the south (Figure 1). This dichotomy has been attributed to orbitally driven variations in solar insolation, analogous to Earth's Croll-Milankovich cycles [3].

Until recently, it was unknown how many of the brighte lacustrine features observed by RADAR were in fact filled with liquid. The VIMS and ISS instruments, which observe at visible and near-infrared wavelengths and thus are sensitive to micrometer-deep pools of liquid hydrocarbon (as opposed to RADAR which can see through ~100 m of liquid methane/ethane [4]), had limited visibility of the north polar terrain during Titan's northern winter. As Titan's approaches northern summer solstice, the VIMS and ISS instruments are obtaining high-quality data of the lake district. We use recent infrared mosaics, acquired with ISS and VIMS, to determine which lacustrine features are filled with liquid and which represent what are likely saturated mud-flats (Figure 2).



Lake Feature	Global	North (55°N-90°N)	South (55°S-90°S)
Swath Coverage	59%	81%	67.0%
Filled / Partially Filled / Empty	1.1% / 0.1% / 0.3%	12% / 0.9% / 1.3%	0.3% / 0.1% / 1.2%

Figure 1: Distribution of hydrologic features on Titan from a combination of RADAR, VIMS, and ISS data.

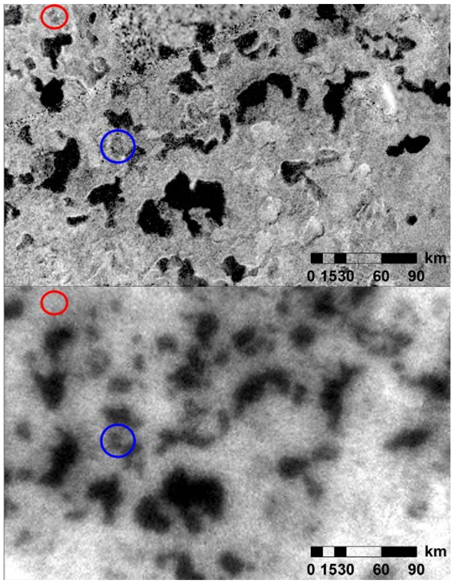


Figure 2 Comparison of SAR (top) and ISS (bottom) observations of Titan's polar terrain. While dark lakes show a one-to-one correspondence, partially filled features may be either visible (blue circle) or invisible (red circle) to ISS/VIMS.

Lake/Sea Volume: In May 2013 (T91), the Cassini RADAR collected nadir-pointed altimetry data across Ligeia Mare. The relatively low flyby altitude, combined with algorithmic suppression of the lateral lobes of the strong surface reflection permitted the detection of subsurface echoes reflected from the bottom of the sea (Figure 3) [4]. Coherent processing of these echoes revealed the bottom reflection along the entire 300 km track across Ligeia and allowed construction of a bathymetry profile [4]. In addition, the relative variations in received subsurface power provided an estimate of the liquid loss tangent ($\tan\Delta=3\pm1\mathrm{x}10^{-5}$) [4] and the magnitude of the surface echo provided an upper limit on sea surface roughness of ~1 mm at the time of data acquisition [5].

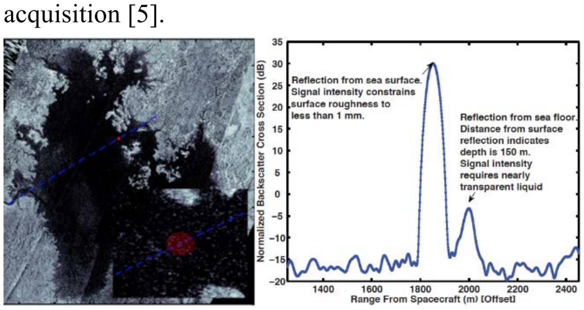


Figure 3: T91 compressed burst over Ligeia Mare from [4] showing the subsurface and subsurface peaks in the echo waveform. The distance between the peaks is the sea depth while the brightness ratio constrains the liquid loss tangent.

Using the bathymetry profile of Ligeia Mare determined by [4], we derive an empircal quasi-specular plus diffuse backscatter function for the seabed return (σ_{bed}) by correcting the average SAR backscatter within the T91 altimetry footprints for liquid attenuation and refraction using the simple two-layer model of [6]. Assuming seabed reflectivity is uniform for other areas of the Mare, this empirical seabed backscatter function is then sed to derive depths for all of the Mare observations that show SAR returns above the instrument noise floor. The two-layer model is given by:

$$\sigma_{obs} = \sigma_{surf} + \sigma_{bed} e^{-8\pi k d \sec\theta_{bed}/\lambda}$$

where σ_{obs} is the observed normalized backscatter cross section, σ_{surf} is the contribution from the sea surface, σ_{bed} is the contribution from the seabed at incidence $\theta_{bed} = \sin^{-1}(\sin\theta_{obs}/n)$, n and k are the real and imaginary components of the liquid's index of refraction, d is the sea depth, and λ is the wavelength. Analysis of the T91 altimetry observations provides estimates of k and d for each of the altimetry footprints over Ligeia Mare as well as the determination that σ_{surf} was negligible, thus allowing derivation of σ_{bed} from the average σ_{obs} in each overlapping footprint. The derived values for σ_{bed} can then be used to solve for the parameters of the best-fit quasi-specular plus diffuse backscatter function [7]. For areas outside of the altimetry track, d can then be estimated assuming σ_{surf}~0 and that $\sigma_{bed}(\theta_{bed})$ is spatially uniform and well-described by the empirically derived backscatter function. Figure 4 shows the results of applying this model to 6 SAR swaths that cover Ligeia Mare. In regions where SAR observations overlap, the depths varied by less than 15% between observations that varied in incidence angle by over 20°. Based on this analysis, the volume of Ligeia Mare is ~14,000 km^3. Extrapolating this analysis to all of Titan's Mare produces an estimated volume of ~70,000 km^3, equivalent to 15 times the volume of Lake Michigan, and 55 times the volume of proven oil reserves on Earth [8].

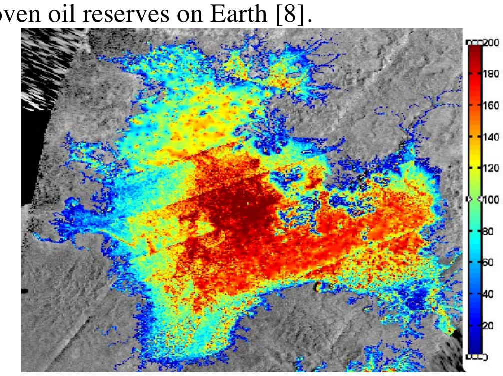


Figure 4: Bathymetry of Ligeia Mare as determined by backscatter modeling of 7 SAR swaths.

References: [1] Stofan E.R. et al. (2007) *Nature*, *445*, 61–64. [2] Hayes A.G. et al. (2008) *GRL, 35,* L09204. [3] Aharonson O. et al. (2009) *Nat. Geo.*, *2*, 851–854. [4] Mastrogiuseppe M. et al (2014) *GRL*, *submited*. [5] Zebker H.A. et al. (2014) *GRL*, *accepted.* [6] Hayes A.G. et al. (2011) *Icarus*, *211*, 655–671. [7] Wye L.C. et al. (2007) *Icarus, 188*, 367–385. [8] CIA Factbook (2009).