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RESEARCH LETTER

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Key Points:

- Ligeia Mare, like Ontario Lacus, is flat with no evidence of ocean waves or wind
- The sea surface dielectric constant suggests a largely methane composition
- Radiometric observations point to solid organic, not water ice, land surface

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Surface of Ligeia Mare, Titan, from Cassini altimeter and radiometer analysis

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Abstract Cassini radar observations of the surface of Ligeia Mare collected during the 23 May 2013 (T91) Cassini flyby show that it is extremely smooth, likely to be mostly methane in composition, and exhibits no surface wave activity. The radar parameters were tuned for nadir-looking geometry of liquid surfaces, using experience from Cassini's only comparable observation, of Ontario Lacus on 21 December 2008 (T49), and also include coincident radiometric observations. Radar echoes from both passes show very strong specular radar reflections and limit surface height variations to 1 mm rms. The surface physical temperature at 80°N is 92 ± 0.5 K if the sea is liquid hydrocarbon and the land is solid hydrocarbon, essentially the same as Cassini CIRS measurements. Furthermore, radiometry measurements over the surrounding terrain suggest dielectric constants from 2.2 to 2.4, arguing against significant surface water ice unless it is extremely porous.

1. Introduction

Saturn's moon Titan remains the only likely planetary body besides Earth in our Solar System whose surface presently exhibits significant accumulations of liquids [Stofan *et al.*, 2007; Hayes *et al.*, 2008] and appears to depict a history of fluvial processes [Jaumann *et al.*, 2008; Burr *et al.*, 2009; Aharonson *et al.*, 2009]. Titan's lakes and seas probably contain mainly ethane and methane [Elachi *et al.*, 2004; Lunine and Lorenz, 2009] and could be evidence of a global hydrocarbon cycle that transports liquids between the polar and equatorial regions. Transport of surface liquids by evaporation, advection by wind, and precipitation back onto the surface, on both seasonal and astronomical [Aharonson *et al.*, 2009] timescales, is captured in many global climate models [e.g., Mitchell, 2008; Schneider *et al.*, 2012]. These models also predict wind speeds during summer that are large enough to stir waves detectable by remote sensing.

Here we present new observations of the surface of Ligeia Mare, Titan's second largest liquid body, collected during the 23 May 2013 (T91) Cassini flyby. During this encounter, the radar parameters were tuned for nadir-looking geometry of liquid surfaces, using experience from Cassini's only comparable observation, of Ontario Lacus on 21 December 2008 [T49, Wye *et al.*, 2009]. We extend the Wye *et al.* analysis not only with an optimized radar configuration, but also by incorporating the simultaneous radiometric brightness measurements that yield the surface dielectric constant and its physical temperature. These two radar passes over the two lakes both show very strong specular radar reflections, suggesting that the surface is mm-level flat, all but ruling out the existence of ocean waves at the time of the observations. Here we show that Cassini's passive radiometric measurements, obtained coincident with the active scans, restrict the surface physical temperature to 92 ± 0.5 K if the sea is liquid hydrocarbon and the land is solid hydrocarbon. This range is essentially identical to Cassini CIRS measurements at 80°N extrapolated to the 2013 epoch and consistent with 2013 preliminary CIRS results. Similar measurements over the surrounding terrain imply a range of 2.2–2.4 for its dielectric constant. Since water ice has a dielectric constant of 3.2, it can have no significant surface presence unless it is extremely porous, thus lowering the bulk dielectric constant.

2. Radar Technique and Observations

The magnitude of radar echoes depends primarily on dielectric constant, surface roughness, and surface slope distributions. Electrical properties of several Titan surface candidate materials in the microwave domain (the Cassini radar operates at 2 cm) are listed in Table 1. Liquid hydrocarbons have rather low dielectric

Table 1. Dielectric Constants and Loss Tangents of Likely Materials on Titan and Earth [Thompson and Squires, 1990; Lorenz et al., 2003]

	Dielectric Constant Magnitude		Loss Tangent
	ε		tan δ ~ Im(ε)/Re(ε)
Most liquid hydrocarbons	1.6–1.9		10 ⁻⁵ –10 ⁻³
Liquid methane	1.7		10 ⁻⁵ –10 ⁻³
Liquid ethane	1.9		10 ⁻⁵ –10 ⁻³
Solid hydrocarbons	2–2.4		10 ⁻⁵ –10 ⁻²
Water ice	3.2		<10 ⁻⁵
Earth soils	3–9		10 ⁻²
Earth seawater	100		~1

constants ranging from 1.6 to 1.9, solid hydrocarbons from 2 to 2.4, while water ice has a value of 3.2 at Titan surface temperatures. For comparison, we include values of Earth soils and seawater, where polar molecules in liquid water lead to much higher dielectric constants.

Roughness and slope affect backscatter magnitude, particularly in near nadir-looking geometries, by affecting the degree to which radar echoes, across the illuminated antenna footprint, add in phase from different points on the surface. If the round trip signal path to a collection of scattering facets on a surface varies by less than about a one fourth of the radar wavelength, the wavelets will add in phase, leading to an echo that looks like a scaled version of the transmitted signal and with a large radar cross section. If, on the other hand, the path lengths differ by a wavelength or more, the waves will often interfere destructively and the observed signal will be weaker and less well defined (Figure 1a).

During Titan pass T91 we collected radar altimeter echoes and radiometric scans in nadir-looking geometry as the satellite probed the surface in the region of Ligeia Mare (Figure 1b). We examined the 78 radar bursts transmitted in this mode and found 39 that exhibited clear specular returns. The specular echoes matched locations within Ligeia Mare, confirming that the surface of the sea was extremely flat while the surrounding terrain was not. The observed radar cross section from these 78 echoes (Figure 1c) shows that specular returns are roughly 100 times (20 dB) brighter than the diffuse land echoes.

Following Wye et al. [2009], we relate the observed cross section to rms height of the surface using a reflection version of the Huygens-Fresnel principle:

$$\sigma = \frac{\rho\pi a^2 R^2}{(a + R)^2} e^{-(4\pi\sigma_h/\lambda)^2} \tag{1}$$

where σ is the radar cross section and σ_h the rms surface height. Titan’s radius is a , R is the Cassini altitude, λ the wavelength, and ρ is the surface Fresnel reflection coefficient, which depends on dielectric constant. Solutions for rms height (or roughness) dependent on the surface dielectric constant suggest maximum roughness ranging from about 1 to 2 mm rms, a very smooth surface (Figure 1d).

We constrain the dielectric constant by examining the radiometric brightness temperature (T_b) of the lake surface, which is the product of its physical temperature (T_{phys}) and its microwave emissivity (e). If the surface is smooth and in thermodynamic equilibrium, then for nadir-looking geometry $e = 1 - \rho$, a consequence of conservation of energy. In terms of our observables,

$$\frac{T_b}{T_{phys}} = 1 - \left(\frac{\sqrt{\epsilon} - 1}{\sqrt{\epsilon} + 1} \right)^2 \tag{2}$$

In Figure 2 (left), we plot observed T_b as a function of latitude after correction for sidelobes and interfering signals [Janssen et al., 2009]; it is about 90.5 +/- 0.5 K over Ligeia. The brightness temperature falls off toward the sea boundaries, likely due to emission from the sea bottom and the varying depth of the sea [Mastrogiuseppe et al., 2013], though possibly representing a physical temperature variation. The sea temperature is greater than the surrounding land by 2 K, a much greater difference than the relative accuracy of perhaps 0.25 K. Using equation 2 with the north polar brightness temperature $T_{phys} = 92 +/- 0.8$ K derived from the Cassini Composite Infrared Spectrometer (CIRS) [Jennings et al., 2009, 2013], we obtain dielectric constant estimates similar to those expected from liquid and solid hydrocarbon sea and land. Further limiting the physical temperature to 92 +/- 0.5 K neatly reproduces the dielectric constants of hydrocarbon materials (Figure 2 right). Combined with Figure 1d, the corresponding value for surface roughness would be about 1 mm rms.

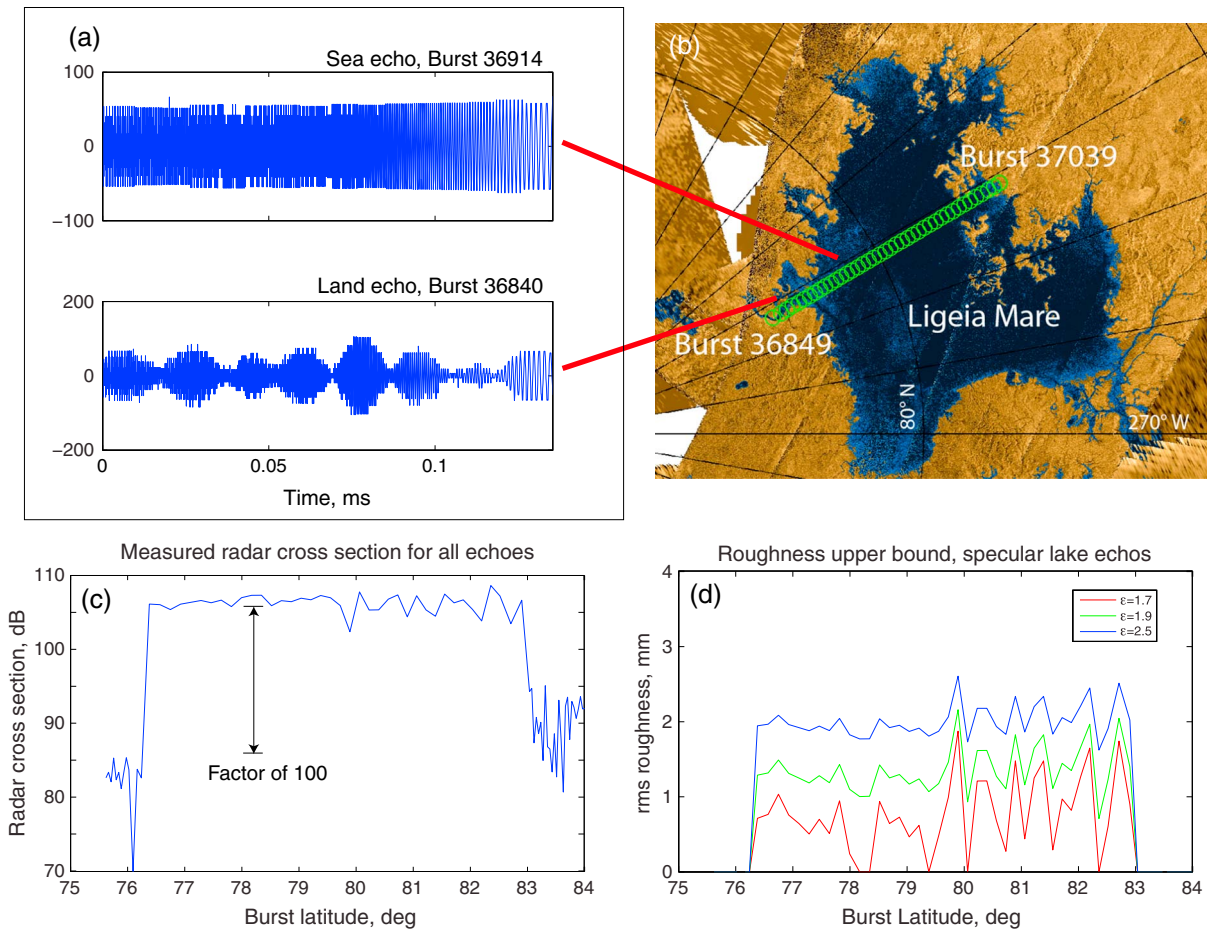


Figure 1. (a) Sample echoes from Cassini pass T91 over (top) sea and (bottom) land showing the “clean” nature of the specular sea echoes. High coherence of reflections from Ligeia surface confirms flatness of the sea, while those received from surrounding terrain are diffuse and interfere destructively. (b) Locations of specular radar altimeter echoes observed on Titan pass T91. (c) Radar cross section vs. latitude — specular echoes from Ligeia are approximately 100 times (20 dB) brighter than the land echoes. (d) Solutions, all rather flat, for rms roughness of Ligeia Mare for several values of surface dielectric constant. Red and green curves ($\epsilon = 1.7$ and 1.9) are plausible values for liquid hydrocarbons, while blue curve ($\epsilon = 2.5$) better represents a solid hydrocarbon surface.

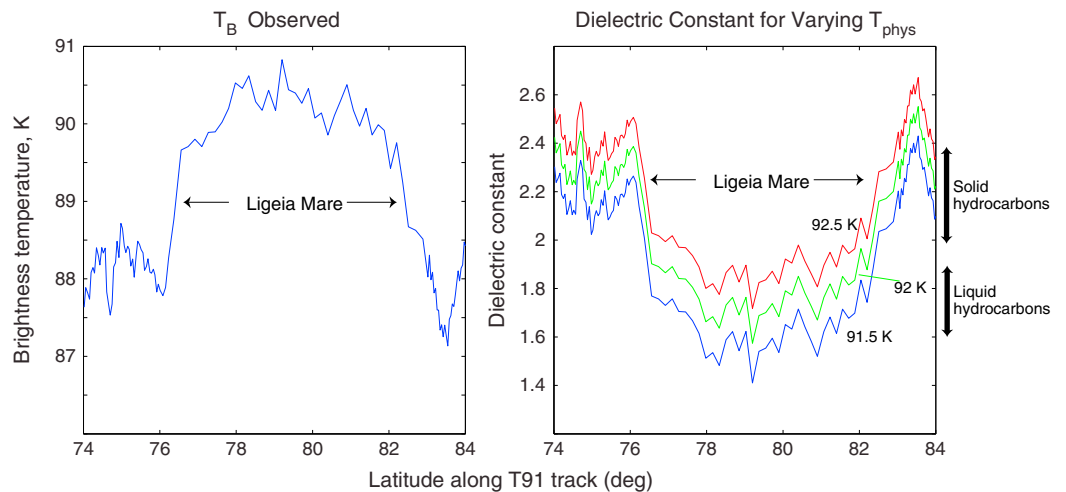


Figure 2. At left, observed brightness temperature of Ligeia Mare region. Right, dielectric constant for several values of physical temperature T_{phys} . Green curve ($T_{phys} = 92$ K) is most consistent with a liquid hydrocarbon sea and solid hydrocarbon land.

3. Discussion and Conclusions

The Cassini T91 data provide conclusions regarding the sea flatness, lack of observable winds, and sea composition. The surface is extremely flat, with rms roughness values ranging from about 0.5 to 1.5 mm over the 100 m Fresnel zone of the radar beam (middle curve, Figure 1d). This is far smoother than most surfaces on Earth, where the only common surface with similar smoothness is likely to be a very flat lake surface. Terrestrial roughness of “smooth” solid terrain ranges from sub-cm to 10’s of cm relief [Schaber *et al.*, 1976], with the smoothest terrestrial land surfaces found in playas as flat as 6 mm rms [Shepard *et al.*, 2001]. Very locally, over 30 cm size patches, dry lakebeds can produce regions with mm-level roughness [see Archer and Wadge, 1998]. Ligeia Mare, on the other hand, is over 100 km in each dimension. This supports our conclusion that the seas and lakes are indeed liquid bodies.

This second observation of lake surface height variation on Titan, after the first of Wye *et al.* [2009], finds that Ligeia Mare was at least as flat as Ontario Lacus was in 2009. The present result is stronger than the first, as the radar parameters were optimized for reception of very strong specular signals, which saturated the receiver during the Ontario encounter and required an indirect gain inference from the shape of the echo histogram. Thus, we obtain a tighter bound on the roughness, 1 mm rms vs. an upper bound of 3 mm rms. Wye *et al.* relied on the saddle-shaped histogram resulting from a saturated receiver to identify the unexpectedly strong specular sea echoes, while here we could more reliably examine the echoes for mutual interference from scattering facets at varying heights.

Since the T49 Ontario observation, the slope distribution of some northern lakes and seas has been constrained by specular reflection of the sun in the near-infrared [Stephan *et al.*, 2010; Barnes *et al.*, 2011; Soderblom *et al.*, 2012]. The T91 and T49 radar altimeter observations indicate that the lake surfaces are essentially flat over the 100 m scale size of the radar altimeter Fresnel zone; furthermore, they recur every burst observation as Cassini covers Ligeia and Ontario. We cannot readily constrain waves with wavelengths in the km and greater range, although km-scale surface slopes must be less than the 0.3° beam width of the radar antenna for us to receive specular echoes. That is, the surface could be locally smooth but with a slight tilt due to km waves. These longer wavelength waves could occur if it is possible to generate them with no transfer of energy to shorter-length waves, or if the waves of km and shorter wavelengths are preferentially damped. It is possible that the lack of waves might be due to very high viscosity of the lake liquids or to the presence of surfactants, although we have no other evidence of either of these effects.

These results have direct implications for Titan climate models that predict the presence of wind in the lower atmosphere. The wind speeds over Ligeia Mare and Ontario Lacus, one in the north and one in the south, must be low enough that essentially no waves are generated. Several models of wind wave generation extrapolated to Titan conditions provide constraints on the wind speed. Ghafoor *et al.* [2000] modified an Earth ocean model using Titan gravity and air density environmental conditions, and with our 1 mm roughness bound it limits wind speed to 0.1 m/s or less, independent of fetch. This and other applicable models were examined using Titan parameters by Lorenz and Hayes [2012], who found that viscosity had more impact on threshold wind speed than on wave heights, and their proposed approximation suggests an even tighter bound on wave height than that of Ghafoor *et al.* Wave tank experiments at the Cassini wavelength [Donelan and Plant, 2009] found that a threshold wind velocity of about 1 m/s was required to raise measurable waves on Earth. Hayes *et al.* [2013] extrapolated the work of Donelan and Pierson [1987] to estimate a range of 0.4–0.7 m/s for threshold winds on Titan, and they also estimated surface wind fields. Both Cassini altimeter passes over lakes/seas occurred when little wind is expected from their model, although others predict higher winds at these times [Tokano, 2009; Newman *et al.*, 2008]. We conclude that winds over the two liquid bodies are below a few tenths of one m/s at the time of the observations. It is possible that our timing has simply been bad luck [Hayes *et al.*, 2013; Schneider *et al.*, 2012], as we may have happened to sample Titan’s surface at times where the regional wind velocities were low. As of this writing, there is no reported direct evidence for any wave present on a Titan sea or lake.

These data also show that both the liquid and solid terrains in the vicinity of Ligeia Mare are probably hydrocarbon materials, matching the inferred dielectric constants of ~1.75 and ~2.3, respectively. The solid land cannot be primarily water ice in this region as the dielectric constant cannot approach the ice value of 3.2. A water ice land surface would predict $T_{phys} = 95.5$ K, much higher than has been elsewhere recorded, unless the water ice is 50% porous so as to achieve a lower dielectric constant.

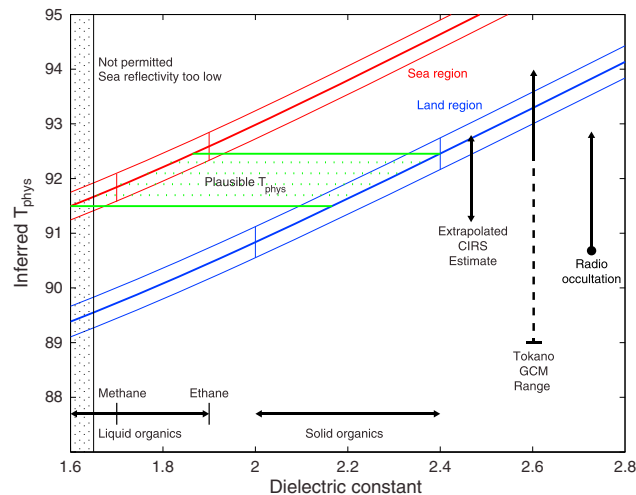


Figure 3. Inferred physical surface temperature T_{phys} for land and sea as a function of dielectric constant. Assuming a solid hydrocarbon land surface with dielectric constant between 2 and 2.4 sets an upper limit of $T_{phys} = 92.5$ K, while a similar constraint on sea surface limits the lowest $T_{phys} = 91.5$ K. Extrapolating CIRS temperature measurements to 2013 yields $T_{phys} = 92 \pm 0.8$ K. A GCM [Tokano, 2005] predicts mostly slightly higher values. The radio occultation observation of $T_{phys} = 90.6$ K on T31 provides a useful lower bound, as Titan has likely warmed roughly slightly more than 2 K since [Schinder et al., 2012]. The center of the plausible range would seem to be closer to the value for a methane sea than ethane.

We summarize estimates of the physical surface temperature T_{phys} in Figure 3. We also show the dielectric constant ranges for solid and liquid organic materials, with specific measurements for both methane and ethane. If we assume a solid hydrocarbon land surface with dielectric constant at most 2.4 we obtain an upper limit of $T_{phys} = 92.5$ K. A similar constraint on sea surface dielectric constant (1.6) limits the lowest plausible T_{phys} to 91.5 K. The center of our range is thus about 92 K, which suggests a dielectric constant slightly greater than that of pure methane, and not close to measured values of pure ethane. The range of consistent T_{phys} makes for a rather loose constraint; nonetheless, the midvalue 1.75 dielectric constant points to a largely methane composition. We note that adding nitrogen, with a yet lower dielectric constant of about 1.5, would permit some ethane in the mixture as well and still be consistent with our measurements.

The CIRS instrument finds variations in temperature of over 2 K for four seasons, northern winter (2004–2006), late northern winter (2006–2008), and early northern spring (2008–2010) [Cottini et al., 2012], and later spring (2013) [Jennings et al., 2013]. Jennings et al. [2009] reported the surface temperature at 80°N during late northern winter as 90.5 ± 0.8 K. Both extrapolating published CIRS results to the 2013 epoch for T91 and preliminary analysis of 2013 data [Jennings et al., 2013] yield a range of 92 ± 0.8 K, nearly the same as our estimate. A global climate model (GCM) due to Tokano [2005] predicts slightly higher values for most scenarios, but permanent haze in the polar atmosphere could lead to a much colder 89 K surface. A radio occultation observation of $T_{phys} = 90.6$ K on T31 provides a useful lower bound, as Titan has likely warmed roughly slightly more than 2 K since [Schinder et al., 2012]. Our experiment provides no evidence for the presence of significant evaporative cooling of the sea.

The temperature structure of the sea surface will depend [Tokano, 2009] on a number of unknown factors, such as the turbidity of the liquid (which influences the depth to which solar energy is deposited), the strength of wind- and tidally driven circulations [e.g., Lorenz et al., 2012], which determine how well-mixed the liquid may be, and the methane/ethane ratio, which together with wind speed, affects evaporation rate. The observations reported here are some of our first insights into Titan as a laboratory for ocean circulation and air-sea exchange processes. Understanding these processes and effects will be important in elucidating Titan's hydrological cycle and its influence on climate.

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