COMPOSITION OF LIGEIA MARE, TITAN, FROM CRYOGENIC LABORATORY MEASUREMENTS AND BATHYMETRY. K. L. Mitchell[1], M. Barmatz[1], C. S. Jamieson[1,2], R. D. Lorenz[3], [1]Jet Propulsion Laboratory, California Institute of Technology, Mail Stop 183-801, 4800 Oak Grove Dr., Pasadena, CA 91109, [2]SETI Institute, Mountain View, CA, [3]Johns Hopkins University Applied Physics Laboratory, Laurel, MD.

Introduction: No direct measurements of the material composition and abundances of Titan's lakes and seas have been possible to date. While VIMS spectra confirm the presence of liquid ethane in Ontario [1], the instrument was incapable of estimating its abundance or distinguishing liquid from atmospheric methane. Rainfall on Titan is thought to consist primarily of liquid methane containing maybe 25% dissolved nitrogen [2] and less significant fractions of other materials, including ethane and propane. However, the volatile methane will evaporate over time, and so the non-methane components are expected to dominate persistent liquid deposits. Thus, the composition of Titan's lakes is likely a mixture of ethane, methane, some propane and nitrogen, and smaller abundances of higher order hydrocarbons and nitriles [3,4]. Assuming thermodynamic equilibrium at 90K, the methane to ethane ratio of a surface lake is 1:8 [3], and so it's possible that lakes could be almost completely depleted in methane. However, the volatile methane will evaporate over time, and so the non-methane components are expected to dominate persistent liquid deposits.

This inability to obtain lake composition data impedes our ability to understand Titan's evolution and the nature of its carbon cycle. In particular, knowing the relative abundances of methane and ethane, the latter of which is far less thermodynamically stable on the surface but also produced at far lower rates, would allow important constraints to be set on evaporation rates, and would be an indirect indicator of longevity of liquid reservoirs.

One possible approach to solving this problem involves looking at how radar backscatter of seas varies with depth, and thus determine the loss tangent (in effect, the opacity) of the liquids. This could then be tested for consistency with the measured dielectric properties of different materials.

Previous laboratory studies. The most recent measurements [6] of Liquified Natural Gas (LNG), a methane-dominated mixture of materials considered to be a reasonable analogue to Titan's hydrological fluids, showed a loss tangent, $\tan\delta_{LNG} \sim 1.14 \times 10^{-3}$, which is greater than previous measurements of liquid alkanes of $10^{-5} < \tan\delta < 10^{-3}$ [7]. This broad range of results means that there is considerable uncertainty in how far Cassini RADAR can "see through" a liquid, with a loss tangent of 10^{-5} permitting observations in nominal SAR model down to hundreds of metres, as opposed to 10^{-3} permitting only a few metres. At this stage, it is unclear whether the differences are due to compositional variation, which in itself would be useful, or experimental limitations or error.

Previous Cassini RADAR analyses. Previously, the only data-derived loss tangent on Titan was part of an analysis of Ontario Lacus [8], which was consistent with the LNG loss tangent of Paillou et al. [6]. That study used indirect modeled bathymetry, thus introducing an unknown uncertainty. However, more recently, Mastrogiuseppe *et al.* [7] were able to use a Cassini RADAR altimetric profile across Ligeia Mare to perform far more direct bathymetry, and their results, in stark constrast with those of Hayes *et al*. [8], showed depths of >100 m, and their derived loss tangent, tan $\delta_{Ligeia} = 3 \pm 1 \times 10^{-5}$, is inconsistent with the measurement of Paillou *et al.* [6].

Experiment method: We have developed a new technique for measuring radar properties of cryogenic liquids, and have used this to measure complex dielectric constants for methane and ethane. We use a cylindrical cavity containing a cylindrical quartz tube, filled with pure methane or ethane situated along the cavity axis, and excite it in TM0n0 modes, where the $n = 2$ mode had a resonant frequency of ~14 GHz at 90K, close to that of Cassini RADAR's Ku-band. Calibration requires measurement of cavity resonant frequency and quality factor for the empty cavity, the inserted empty tube, and the tube filled with a hydrocarbon liquid. These quantities are determined by fitting the measured amplitude versus frequency curve with a Lorentzian line shape. From this, it is possible to derive both real and imaginary dielectric constants, and hence loss tangent.

Our sample scale is comparable to, or less than, the scale of the wavelength (2.17 cm) of Ku-band. This is a huge advantage over previous methods in terms of both thermal equilibration times and control, as well as the relatively low amounts of cryogenic liquids used, and hence cost.

To date, eight runs have been performed using pure methane and ethane, both at $n = 1$ (~6.4 GHz) and $n = 2$ (~14.1 GHz) modes, with results summarized in Table 1. Of these, some results have been deemed invalid due to experimental errors, both from direct evidence (fitting the Lorentian line shape was impossible, indicating issues with cavity symmetry) and indirect (results are an outlier, and statistical tests, such as Dixon's Q-Test, show that they are significantly inconsistent with previous results, yielding six-to-seven

"good" runs for each type of measurement. Uncertainties in results have been determined analytically (err. 2 column in Table 1), and are the result of errors in Lorentzian line shape fit, as well as conservative estimates of uncertainties in cavity radius and quartz tube dimensions. We have also determined statistical RMS errors (err. 1 in Table 1).

Results: In both analytically derived and RMS errors, uncertainties are greater where absorption is weaker, thus higher for methane than ethane. There is a reasonable correlation between the two error types which strengthens confidence in our results (Table 1). The lower RMS errors are thought to be the result of conservative over-estimations of geometric uncertainties. RMS errors are quoted henceforth.

Our measurements fall generally within the envelope of previous studies, albeit with imaginary components at the lower end. Our determined loss tangent for liquid methane, $\tan \delta_{CH4,n=2} = 2.71 \pm 0.54 \times 10^{-5}$, is in extremely good agreement with that determined for Ligeia Mare by Mastrogiuseppe et al.: $\tan \delta_{Ligeia} = 3 \pm 1 \times 10^{-5}$. In contrast, the loss tangent measured for ethane, $\tan \delta_{C2H6,n=2} = 1.13 \pm 0.04 \times 10^{-4}$, is well outside of experimental error. We consider it unlikely, given liquid methane's extremely low loss tangent, that mixing or dissolving other materials with methane would result in an decrease of loss tangent.

Discussion: It is difficult, given these numbers, to avoid the conclusion that methane is the dominant constituent of Ligeia Mare. While not inconsistent with the notion of volatiles accumulating in the north during the present climate epoch [5], this is a challenge to thermodynamic equilibrium models of sea composition [3].

This conclusion incorporates several assumptions, namely: (1) That dissolved compounds do not significantly modify the bulk dielectric properties; and (2) That the radar properties are either not influenced by minor constituents, or are influenced in a manner that can be predicted by a simple linear mixing model. We know of no reason to doubt these assumptions, but future experiments will test them.

More generally, the ~5× difference means that it should be possible to constrain, to some extent, the compositions of Titan's lakes and seas, if indeed methane and ethane are not only the main constituents but also exert the dominant influence on dielectric properties. Our results enhance the value of Cassini RADAR altimetric overpasses of lakes.

Finally, we note that our results appear to be inconsistent with Paillou et al.'s [6] measurement. Their sample differed from ours, as it was a mixture of materials with >90% methane, but with a range of additional compounds measured in an open-air propagation test that may have led to higher losses that those we observe with pure samples in the cavity. Based on our measurements, and assuming a simple mixing model for methane and ethane, we would have anticipated a loss tangent of $\sim 3.6 \times 10^{-5}$, a mismatch by a factor of >30×. Thus in future work we will explore the effect of mixtures and impurities on dielectric properties, and directly measure samples of Liquified Natural Gas, in order to explain the apparent inconsistency.

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Composition	***n***	**ε'**	**err. 1**	**err. 2**	**ε''**	**err. 1**	**err. 2**	**tan δ**	**err. 1**	**err. 2**
Methane	2	1.60	0.3%	5.1%	4.33×10^{-5}	19.9%	26.0%	2.71×10^{-5}	19.8%	31.1%
Methane	1	1.60	1.9%	7.4%	1.35×10^{-5}	40.6%	72.1%	8.46×10^{-6}	41.6%	80.0%
Ethane	2	1.83	0.4%	4.1%	2.07×10^{-4}	3.0%	4.6%	1.13×10^{-4}	3.1%	8.7%
Ethane	1	1.81	0.6%	5.3%	1.37×10^{-4}	9.9%	16.1%	7.55×10^{-5}	9.9%	21.4%

Table 1: Summary of dielectric properties of cryogenic liquid alkanes determined in this study. Both statistical and analytical errors are given.