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Philippe Paillou, J.I. Lunine, Gilles Ruffié, P. Encrenaz, S. Wall, et al.. Microwave dielectric constant of Titan-relevant materials. *Geophysical Research Letters*, 2008, 35 (18), pp.L18202. 10.1029/2008GL035216 . hal-00319723

HAL Id: hal-00319723

<https://hal.science/hal-00319723>

Submitted on 16 Aug 2021

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Microwave dielectric constant of Titan-relevant materials

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Received 2 July 2008; revised 25 August 2008; published 24 September 2008.

[1] For four years, the Cassini Radar instrument has slowly revealed the surface of Titan. It has discovered cryovolcanic flows, craters, dunes, channels, rivers, lakes and seas. In order to analyze and model the microwave behaviour of Titan's surface, we need to know the dielectric constant of its surface materials. We present here Ku-band (10 and 13 GHz) measurements of the dielectric constant of various materials that are likely to be present on Titan. Most of the measured values are in the 1.5–4.3 range with a very low loss tangent (less than 10^{-2}), consistent with results obtained from the Radar scatterometer and radiometer modes, indicating that the Cassini Ku-band Radar should penetrate several meters of Titan's surface. **Citation:** Paillou, P., J. Lunine, G. Ruffié, P. Encrenaz, S. Wall, R. Lorenz, and M. Janssen (2008), Microwave dielectric constant of Titan-relevant materials, *Geophys. Res. Lett.*, 35, L18202, doi:10.1029/2008GL035216.

1. Introduction

[2] Saturn's moon Titan is the second largest satellite in the solar system and the only moon with a thick atmosphere. Since 2004, instruments onboard the Cassini-Huygens mission have slowly revealed its surface. Playing a particularly important role, the Ku-band (13.78 GHz–2.18 cm) Radar instrument [Elachi *et al.*, 2004] is able to image Titan's surface through its atmosphere. Tens of flybys over Titan have been performed by the Cassini spacecraft so far, mapping a very geologically diverse and young landscape, with dome-like volcanic features, fluvial and dendritic channels, large longitudinal dune fields, lakes and seas [Elachi *et al.*, 2005, 2006; Lopes *et al.*, 2007a, 2007b; Lorenz *et al.*, 2006, 2007, 2008a; Lunine *et al.*, 2008; Radebaugh *et al.*, 2007, 2008; Stofan *et al.*, 2007].

[3] From the Radar instrument point of view, scattering properties of Titan's surface range from very low return (e.g., lakes, backscattered power lower than 20 dB) to very high return (e.g., cryovolcanic flows, backscattered power higher than 0 dB). Even if surface slope and roughness are the main parameters that control the backscattered power

[Ulaby *et al.*, 1982], the dielectric constant of the surface material needs also to be known in order to help data analysis and inversion: this parameter controls the reflectivity of the surface but also the radar penetration depth in the material [Ulaby *et al.*, 1982]. Its knowledge will also help determine the structure of the surface material (porosity, fracturation) from the study of the volume scattering component [Zebker *et al.*, 2008; M. A. Janssen *et al.*, Titan's surface at 2.2 cm wavelength imaged by the Cassini RADAR radiometer: Calibration and first results, submitted to *Icarus*, 2008].

[4] At the surface, Titan's temperature is about 94 K and its surface materials mainly consist of hydrocarbons. A liquid phase of methane – ethane mixture is likely to fill in the lakes and seas [Stofan *et al.*, 2007; Mitri *et al.*, 2007, Lorenz *et al.*, 2008b], with some small amount of nitrogen and propane [Lunine, 1992]. A solid phase, in the form of photochemically-produced “tholins”, is likely to constitute the equatorial dune fields [Paganelli *et al.*, 2007; Radebaugh *et al.*, 2007; Lorenz *et al.*, 2008b]. Other components can also be mixed in small (1–100 ppm in the liquid) quantities into the surface and seas of Titan, such as benzene, ethylene, acetylene, butane, propane, heptane, cyclohexane, nitrogen and carbon dioxide ice [Lunine, 1992; Dubouloz *et al.*, 1989; Wilson and Atreya, 2004]. Large amount of water-ammonia ice should also be present on Titan, since it might have been produced in areas where cryovolcanism has occurred [Tobie *et al.*, 2006; Hayne *et al.*, 2008].

[5] Most of the dielectric constants of Titan-relevant materials that can be found in the literature only give the real part of this parameter or present a high uncertainty on the imaginary part. They were generally measured at frequencies lower than the Ku-band and at room temperature [Whiffen, 1950; Lorenz, 1998; Lorenz and Shandera, 2001; Lorenz *et al.*, 2003]. Using free-space and resonant cavity methods, we measured the complex dielectric constant of various materials of interest for Titan, at liquid nitrogen temperature (77 K) and at the Ku-band frequencies of 10 and 13 GHz. The obtained values are in the range of the dielectric constant of Titan's surface derived from radiometer and scatterometer measurements [Wye *et al.*, 2007; Zebker *et al.*, 2008; Janssen *et al.*, submitted manuscript, 2008], and will be useful to help the interpretation, inversion and modeling of Cassini Radar data.

2. Measurement of the Dielectric Constant of Titanian Materials

[6] We considered materials that can be easily obtained and manipulated in a laboratory environment, cooled by liquid nitrogen in order to remain in the temperature range at Titan's surface. Instead of liquid methane, we used Liquefied Natural Gas (LNG) which contains more than

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Table 1. Measured Dielectric Constant, Computed Loss Tangent and Penetration Depth of Titan-Relevant Materials at 10 GHz and 13 GHz at Liquid Nitrogen Temperature^a

Material ^b	Method ^c	Real (Dielectric Constant) ϵ'	Imag (Dielectric Constant) $\epsilon'' \times 10^{-3}$	Loss Tangent (ϵ''/ϵ') $\times 10^{-3}$	Penetration Depth in m (13.78 GHz)
Water ice (S)	R	3.13	1.3	0.41	4.72
Water ammonia ice (1.75% NH ₃) (S)	R	3.17	1.8	0.57	3.43
Water ammonia ice (3.5% NH ₃) (S)	R	3.21	2.1	0.65	2.96
Water ammonia ice (7% NH ₃) (S)	R	3.38	2.7	0.79	2.36
Water ammonia ice (14% NH ₃) (S)	R	3.58	3.1	0.87	2.11
Water ammonia ice (28% NH ₃) (S)	R	4.38	4.2	0.96	1.73
LNG (90% CH ₄) (L)	F	1.75	2.0	1.14	2.29
Butane C ₄ H ₁₀ (L)	F	1.82	2.8	1.54	1.67
Benzene C ₆ H ₆ (S)	R	2.38	2.2	0.92	2.43
Heptane C ₇ H ₁₆ (S)	R	1.97	3.2	1.62	1.52
Cyclohexane C ₆ H ₁₂ (S)	R	2.10	0.8	0.38	6.28
CO ₂ ice (S)	R	1.55	0.3	0.19	14.38
N ₂ (L)	F	1.45	0.2	0.14	20.86
Tholins 1 compacted (S)	R	2.03	22.0	10.84	0.22
Tholins 2 powder (S)	R	1.17	3.3	2.82	1.14
Tholins 2 compacted (S)	R	2.33	20.6	8.84	0.26

^aResonant cavity method is at 10 GHz and free-space method is at 13 GHz. Liquid nitrogen temperature is 77 K.

^bS is solid and L is liquid.

^cR is resonant cavity and F is free-space.

90% pure methane (CH₄) [Paillou *et al.*, 2008]. Heavier alkanes such as benzene (C₆H₆), butane (C₄H₁₀), heptane (C₇H₁₆) and cyclohexane (C₆H₁₂) were also considered. We measured the dielectric constant of water-ammonia ice, with NH₃ concentration varying from 0 to 28%. Finally, other materials such as laboratory-produced tholins, carbon dioxide ice (CO₂) and liquid nitrogen (N₂) were characterized.

[7] We used both a free-space method, based on 13 GHz focused elliptical antennas [Ghodgaonkar *et al.*, 1989; Paillou *et al.*, 2008], and a 10 GHz resonant cavity method [Vaid *et al.*, 1979; Rodriguez *et al.*, 2003] with a vector network analyzer ANRITSU 37325A in order to measure the dielectric constant (relative complex permittivity) $\epsilon = \epsilon' - j\epsilon''$ of these materials. We estimate the measurement error to about 10% on the real part and 20% on the imaginary part of the dielectric constant, for both methods. Measurement results are summarized in Table 1.

[8] Tholins can be produced in a laboratory environment by irradiation with UV light, electrical discharge or energetic electrons of a gas mixture close to Titan's atmospheric conditions (nitrogen with 2 to 10% methane at a pressure of 1 to 3 mbars) [Coll *et al.*, 1999; Szopa *et al.*, 2004]. Earlier measurements at 10 GHz of compacted tholins produced from an atmosphere containing 2% methane by Rodriguez *et al.* [2003] are recalled in Table 1 ($\epsilon = 2.03 - j0.0220$). We performed new measurements of tholin samples produced using a radio frequency plasma discharge system [Szopa *et al.*, 2004]. Tholin samples (powder with 1 μm mean grain size) obtained from a 2% methane atmosphere were measured in two states using a resonant cavity: non-compacted ($\epsilon = 1.17 - j0.0033$) and compacted ($\epsilon = 2.33 - j0.0206$) samples. The dielectric constant of compacted samples is higher since they contain less air. Also, compaction increases the imaginary part of the dielectric constant by a factor 6, indicating an increase in conductivity. The dielectric constant of various alkanes was measured using both resonant cavity and free-space methods. LNG containing more than 90% liquid methane was previously measured at $\epsilon = 1.75 - j0.0020$ [Paillou *et al.*, 2008]. We obtained a value $\epsilon = 1.82 - j0.0028$ for butane (C₄H₁₀) using the free-

space method. The resonant cavity allowed us to obtain values of $\epsilon = 2.38 - j0.0022$ for benzene (C₆H₆), $\epsilon = 1.97 - j0.0032$ for heptane (C₇H₁₆), and $\epsilon = 2.10 - j0.0008$ for cyclohexane (C₆H₁₂). These values are in the range of results obtained by Sen *et al.* [1992] for alkanes at a lower frequency (1.2 GHz). We also measured the dielectric constant of carbone dioxide ice using the resonant cavity ($\epsilon = 1.55 - j0.0003$) and the dielectric constant of liquid nitrogen ($\epsilon = 1.45 - j0.0002$) using the free-space method, the latter value being consistent with previous measurements [Smith *et al.*, 1991]. Finally we produced samples of water-ammonia ice containing 0 to 28% of ammonia (NH₃) by diluting a concentrated ammonia solution and cooling the mixture using liquid nitrogen. With the resonant cavity method, we obtained a real part ranging from 3.13 to 4.38 and an imaginary part ranging from 0.0013 to 0.0042 (see Table 1 and Figure 1), the dielectric constant – both real and imaginary parts – increasing with the concentration in ammonia. The values of real part of the dielectric constant

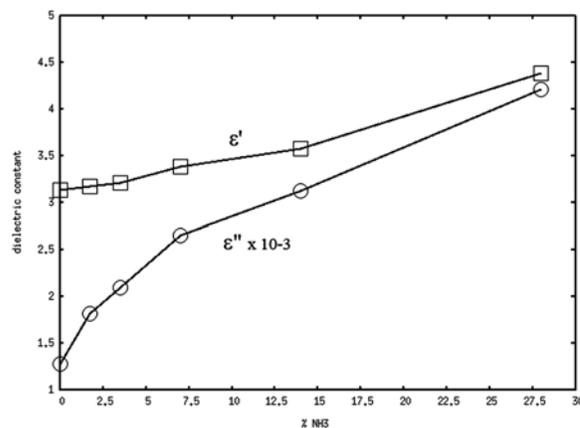


Figure 1. Change in dielectric constant (real and imaginary parts of the relative complex permittivity) of water-ammonia ice with respect to the NH₃ concentration, at 10 GHz frequency and at liquid nitrogen temperature (77 K).

of frozen ammonia solutions we measure at 10 GHz are very similar to the near-DC values determined by Lorenz [1998] at liquid nitrogen temperatures. The loss tangents we report here (less than 10^{-3} , see Table 1) are rather lower than those measured using a microwave oven at 2.45 GHz by [Lorenz and Shandera, 2001], but those measurements were made at dry ice temperatures (i.e., above 193 K) and so likely have a loss contribution from thin films of unfrozen water-ammonia eutectic solution. Thus while our measurements here confirm that ammonia-rich water ice at Titan surface conditions is indeed more lossy than pure ice, it appears that the difference is not dramatic.

3. Discussion

[9] All measured values of the dielectric constant of Titan-relevant materials are in the range of previously published values summarized by Lorenz *et al.* [2003]. However, we present here measurements in the Ku-band of the Cassini Radar instrument, at a low temperature comparable to Titan's surface conditions, and we also measured the imaginary part of the dielectric constant: this allows to compute the loss tangent of the material, and then estimate the penetration depth of the radar. For a homogeneous material of dielectric constant $\varepsilon = \varepsilon' - j\varepsilon''$, the penetration depth of a Ku-band ($\lambda_0 \in = 2.18$ cm) wave can be estimated using the relationship [Ulaby *et al.*, 1982]:

$$\delta_P = \frac{\lambda_0}{4\pi} \left\{ \frac{\varepsilon'}{2} \left[\sqrt{1 + \left(\frac{\varepsilon''}{\varepsilon'} \right)^2} - 1 \right] \right\}^{-1/2} \quad (1)$$

[10] Table 1 shows the computed penetration depth for each characterized material: in most cases, the penetration of a Ku-band wave will be several meters. This means we have to take into account subsurface and volume scattering effects when analyzing Cassini Radar data [Paillou *et al.*, 2006].

[11] One can also observe in Table 1 that the real part of the dielectric constant for all materials is in the 1.5–4.3 range, leading that the reflectivity of Titan's surface should be low. In order to explain the very high backscattering power observed over several places on Titan (e.g., cryovolcanic flows, river channels), one should then consider other effects than single surface scattering: high volume scattering [Wye *et al.*, 2007; Janssen *et al.*, submitted manuscript, 2008], two-layer geometry [Paillou *et al.*, 2006], coherent or multiple scattering [Ostro *et al.*, 1992, 2006], or special geometrical effects such as double-bounce in river canyons for instance.

[12] Our laboratory measurements are consistent with dielectric constant values derived from Cassini Radar scatterometer and radiometer modes. Using the Hagfors model applied on scatterometer data, Wye *et al.* [2007] estimated a regional mean real part of the dielectric constant between 1.9 and 3.6, while Janssen *et al.* [2008] used the calibrated radiometer mode to produce a global dielectric map of Titan, in the 1–3 range. The latter observed a real part of the dielectric constant of about 1.7 for the equatorial dune regions, consistent with a composition of tholins – ice mixture of moderate porosity, and a low dielectric constant value around 1.7 for the radar-dark northern seas, which is consistent with the measurements we obtained for alkanes.

[13] Finally, we note that these measurements have implications beyond Titan. In particular, the Cassini Radar instrument has observed a systematic variation in both backscattered power and brightness temperature across the Saturnian system [Ostro *et al.*, 2006] with the inner (optically brighter) satellites having higher radar albedo and lower emissivity than the outer satellites. One possible interpretation has been that ammonia abundance may be an important factor in controlling these radar properties, but the modest loss tangents we report here suggest that other absorbers, such as tholins, silicates or iron-bearing minerals, are much more effective Ku-band absorbers. Whether mixtures of these materials in ice can simultaneously account for the observed radar and optical properties of the satellites without invoking ammonia, which is radar absorbing but optically bright, must await future modeling efforts.

[14] **Acknowledgments.** The authors are grateful to CNES for financial support of this project and to C. Szopa and G. Cernogora from IPSL laboratory for providing tholins samples. They also thank an anonymous reviewer for his useful comments. Part of the research described in this paper was carried out at the Jet Propulsion Laboratory, California Institute of Technology, under a contract with the National Aeronautics and Space Administration.

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