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Radar Reflectivity of Titan

Duane O. Muhleman, Arie W. Grossman, Bryan J. Butler, Martin A. Slade

The present understanding of the atmosphere and surface conditions on Saturn's largest moon, Titan, including the stability of methane, and an application of thermodynamics leads to a strong prediction of liquid hydrocarbons in an ethane-methane mixture on the surface. Such a surface would have nearly unique microwave reflection properties due to the low dielectric constant. Attempts were made to obtain reflections at a wavelength of 3.5 centimeters by means of a 70-meter antenna in California as the transmitter and the Very Large Array in New Mexico as the receiving instrument. Statistically significant echoes were obtained that show Titan is not covered with a deep, global ocean of ethane, as previously thought. The experiment yielded radar cross sections normalized by the Titan disk of 0.38 ± 0.15, 0.78 ± 0.15, and 0.25 ± 0.15 on three consecutive nights during which the sub-Earth longitude on Titan moved 50 degrees. The result for the combined data for the entire experiment is 0.35 ± 0.08. The cross sections are very high, most consistent with those of the Galilean satellites; no evidence of the putative liquid ethane was seen in the reflection data. A global ocean as shallow as about 200 meters would have exhibited reflectivities smaller by an order of magnitude, and below the detection limit of the experiment. The measured emissivity at similar wavelengths of about 0.9 is somewhat inconsistent with the high reflectivity.

Titan is one of the most interesting objects in our solar system. Although it was discovered in 1655, little was known about it previous to the Voyager 1 flyby in 1980. This flyby supplied us with extensive atmospheric information, including the temperature-pressure profile (*1*), and composition (*2*). The atmosphere consists mainly of N_2 with traces of hydrocarbons and nitriles including ethane, methane, acetylene, and HCN. Methane and CO have also been detected in Earth-based observations (*3*). However, because of its extensive hazy atmosphere, little was learned about the surface of Titan except that the temperature is 94 K, which varies only by a few kelvin from equator to pole (*1, 4*), and the atmospheric pressure is 1.5 bars. Even though the surface data are sparse, they can be combined with thermodynamical data on the chemical species to make important predictions about the state of

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the surface. Because of the cold trap of 70 K in Titan's atmosphere at 42-km altitude, most of the hydrocarbons must condense out there. These condensed hydrocarbons subsequently rain down on the surface, mainly in the form of ethane, acetylene and methane. This leads to the prediction of an icy surface, covered by liquid hydrocarbon oceans up to a kilometer in depth (*5*). Land masses could rise above the ocean surface if topographic relief is sufficiently large, although the cutoff of the Voyager radio signals at occultation ingress and egress yielded surface radii at these two points within 500 m of each other (*1*). The only previous Earth-based detections of Titan's surface were measurements of its microwave emission (*6*), which are somewhat ambiguous as to the state of the surface. The only way to directly study the surface, other than a landing, is with radar. In this, we present evidence for a successful radar detection of Titan [a previous experiment (*7*) yielded equivocal results].

We formed the radar instrument by pairing the transmitter on the NASA/JPL, 70-m antenna in California with the Very Large Array (VLA) in New Mexico, which was the receiving telescope (*8*). Titan may be considered a point surface for this experiment because its diameter is much smaller than the primary telescope beams and a factor of 3 smaller than the beam synthesized at the VLA. The expected echo power is then easy to compute by means of the classic radar equation

$$P_r = \frac{P_t A_t A_r}{4\pi\lambda^2 D^4}\eta\pi R^2 \qquad (1)$$

where P_t = transmitted power 360,000 W; A_t and A_r = effective transmission and reception areas, respectively; R = radius of Titan = 2575 km; D = distance to Titan; and η is a parameter we will call the reflectivity which includes the surface electrical reflectivity and the backscatter gain. Because the receiver system is calibrated with known radio sources, it is convenient to express the results in the natural radio astronomy units of jansky (1 Jy = 10^{-26} W m^{-2} Hz^{-}). Even though the VLA measures power, it effectively divides that power, Eq. 1, by A_r and the back-end channel separation, 381 Hz for our experiment, to get janskys. The calibration technique actually removes A_r from the problem. If Titan is a perfect reflector with η = 1, Eq. 1 yields an echo power of $(2.88 \pm 0.3) \times 10^{-21}$ W for the ephemeris of 3 June 89 and our knowledge of the radar parameters (*9*). If the entire echo came from the subradar point on Titan it would be contained in the central 381-Hz channel and 95 ± 5 mJy would be detected in that channel. If the surface scattering properties of Titan were such that all points on the surface reflected equally, about one third of this would be detected in each of the center three channels which nearly cover the entire rotational frequency spread of our signal (Fig. 1).

The basic goal of this experiment is to measure η and to interpret the result. A very special case of a possible Titan surface structure is a perfectly smooth, homogeneous dielectric sphere for which η depends only on the real part of the dielectric constant. In reality, η is a function of the surface roughness, the transparency of the surface, and the presence of subsurface volume scatterers and possible multiple reflections from interfaces. Relevant values of η for homogeneous spheres are listed in Table 1. Monocrystalline ices of methane, carbon dioxide, and similar frozen volatiles are similar to water ice. These ices in powder form exhibit values of dielectric constant between 1.0 and 3.0, depending on the packing fraction.

It is not clear that the reflectivities listed in Table 1 are relevant to Titan or any of the satellites in the outer solar system in light of the radar experiments performed on the Galilean satellites (*10*). The measured values of reflectivity as defined here range from 1 for Europe, to 0.5 for Ganymede, to 0.25 for Callisto (*10*). These values are all much larger than those in Table 1 even though the surfaces

Table 1. Reflectivity of smooth homogeneous dielectric spheres.

Substance	Dielectric constant	Reflectivity, η
Monocrystalline H_2O ice	3.1	0.076
Mean lunar regolith	2.75	0.061
Mean venusian "regolith"	4.0	0.111
Liquid ethane	1.8	0.021

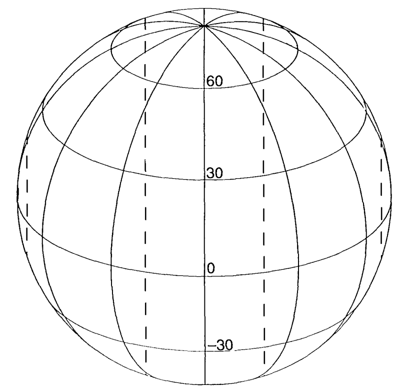

Fig. 1. Apparent geometry of Titan for 4 June 1989. The dashed lines are the edges of the Doppler strips for the resolution of 381 Hz assuming that Titan rotates synchronously with respect to Saturn.

are predominantly ice. There is an enhanced backscatter gain for the Galilean satellites related to the penetration of the radar waves into the highly transparent, cold icy surfaces. The results of this paper suggest that a similar phenomenon is occurring on Titan. A similar effect was found by the authors for radar reflection for the martian south polar residual ice cap (*11*).

Observations

Titan was observed on the nights of 3, 4, 5, and 6 June 1989 as the satellite moved from eastern elongation to a point nearly south of Saturn. Titan was too close to Saturn on the last night to yield useful data because the thermal emission from the planet confused the Titan measurements. Monochromatic signals were continuously transmitted toward Titan from the 70-m antenna at a frequency of 8.495 GHz, with a nominal power of 360,000 W. The JPL Titan ephemeris was used to point the individual antennas. We periodically checked the pointing angles for the 70-m antenna using the radio emission from Saturn. The full width at half power for that telescope is 125 arc sec and the root-mean-square (rms) pointing errors have been measured to be ±18 arc sec (*12*). The pointing of the VLA antennas was even less critical since the beams are much larger and scans of the nearby calibration source at 30-min intervals tended to correct for pointing errors. The consistency of the measured thermal emission of Titan over the experiment confirms this. The flux from Titan including the radar energy and the satellite's thermal emission was collected at the VLA. The VLA was in the C configuration with a maximum separation among the twenty-seven 25-m telescopes of about 3 km. The synthesized resolution of the VLA was about 2.5 arc sec, which is large compared to the angular diameter of Titan and the uncertainty of the Titan ephemeris; that is, Titan was a point source of known position. The exact transmitter frequency was adjusted such that the Doppler shift on the Titan radar echo at the VLA was always zero. The electronic phase of the VLA was continuously adjusted to "point to" the ephemeris position of Titan. Consequently, Saturn was always moving through the fringes which minimized the confusion from the strong thermal emission from the planet. We measured the Titan flux using the spectrometer mode of the VLA with the narrowest channels available, 63 channels with separations of 381 Hz. The rotation of Titan caused the monochromatic transmitted signal to be spread to about 1200 Hz yielding three channels capable of collecting the radar echo energy in the geometry shown in Fig. 1. We have assumed planet-synchronous rotation of Titan. The Titan thermal emission appears in all 63 narrowband channels, as well as in a broadband channel of width 145,000 Hz.

A strong Quasi-Stellar-Object (QSO), P1908-201, was observed at half-hour intervals at the VLA to calibrate the amplitude and phase (position) of the instrument (*13*). Titan was treated like an ordinary radio source in the data reduction process. Each night's 5-hour run was calibrated with P1908 as a calibration source of known flux density and spatial position. The field containing Titan was mapped for each run by computing the Fourier transform of the observed visibilities. Maps for each night were made for the broadband continuum channel which show the thermal emission from Titan in the center pixel as well as smeared images of the Saturn emission well away from Titan. Titan can be seen clearly in the narrowband, central channel map for 4 June because the radar echo was very strong in that case. Since the thermal emission from Titan is less than 3 mJy (see below) and the rms noise in a narrowband spectral channel map is somewhat larger than that, one cannot detect Titan in channels without the radar energy. Maps were computed for inspection in which the flux of Saturn was removed by CLEANING (*14*) the region of the map containing Saturn, that is, by carefully estimating the contribution of the flux from the planet, including serious grating lobes which interfere with the Titan images. The calibrated complex visibilities were corrected for the Saturn visibilities (including side lobes) and all the visibility data were vector averaged for each channel. This yields a single complex number for each channel, an amplitude, and a phase. The set of these estimates constitutes the complex spectrum for the day. The complex spectra for 3, 4, and 5 June are shown in Fig. 2. The radar echo is obvious in at least the central channel for 4 June including a very small phase, which means that the energy in this channel came from within 1 arc sec of the ephemeris position of Titan. The detection of the echo for the other days and channels requires a careful discussion. The phase data for 3 June outside the radar channels appear to be biased by Saturn and the phase of the central channel is 58°. Spectra obtained by averaging the data from all 3 days and from an average of 3 and 5 June are compared to the spectrum for 4 June in Fig. 3. Note the near zero value of the phase in every case.

Detection Measure

An interferometer consists of a pair of antennas characterized by a baseline vector. The VLA operating with 27 antennas constitutes 351 interferometers. The output of the correlator of a single interferometer is a vector whose amplitude is the flux density (for an unresolved point source) and whose phase is the fraction of the fringe lobe that the source is away from the ephemeris position. The ephemeris position is used to adjust the electronic phase of the instrument and, in effect, point the fringes. The output of the correlators consists of the measured signal, along with random noise from fluctuations due to the receivers, cables, the atmosphere, and so forth. For a well-built and calibrated instrument such as the VLA, the mathematical structure of the noise is very close to a normal bivariate distribution of the real and imaginary components of the noise vector which is added to the signal vector. We tested the noise statistics and found that the real and imaginary parts of the data in other than the radar channels are well represented by gaussian distributions with equal variances. When Titan was observed, the

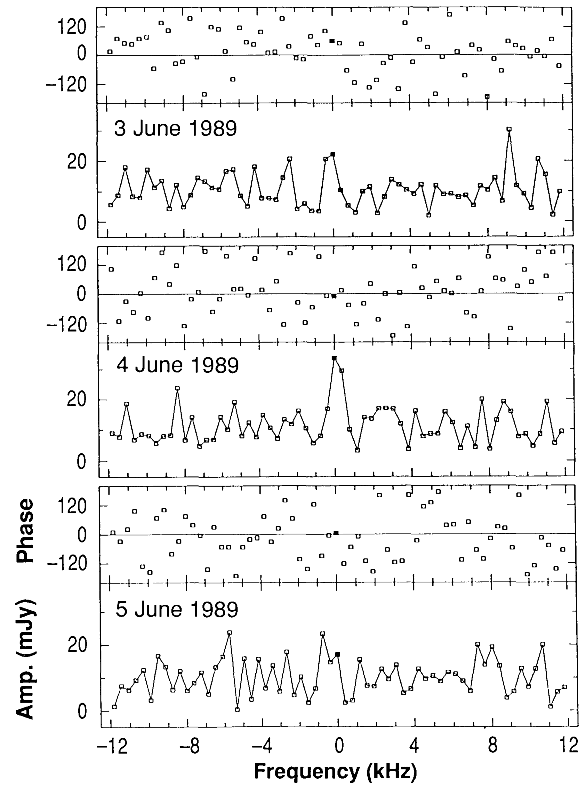

Fig. 2. Complex spectra for 3, 4, and 5 June showing the phase in degrees (upper panels) and the amplitudes in millijanskys (lower panels). The data for channel 0, the central channel in Fig. 1, have been filled in. A zero phase angle means that the energy has come from the ephemeris position of Titan on the sky except for noise fluctuations. A random distribution of phases is expected except in the three center channels which contain radar echo energy.

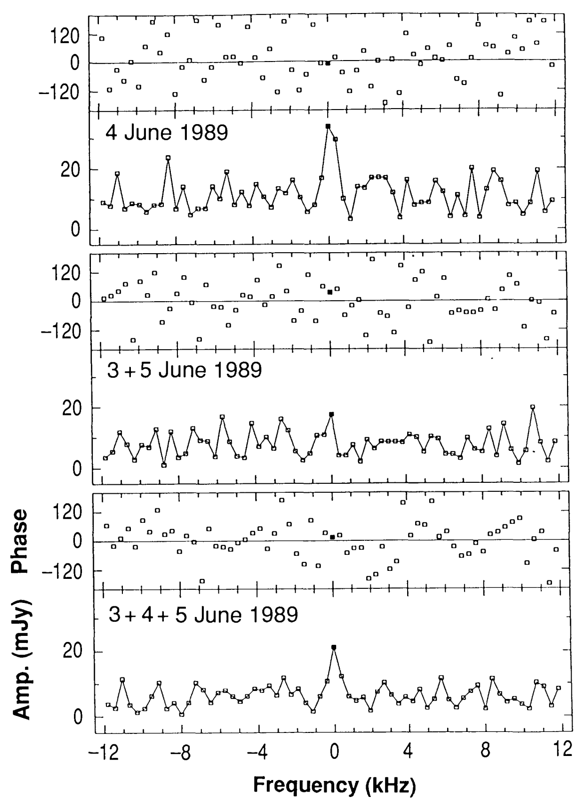

Fig. 3. Same as Fig. 2 except that the spectrum of 4 June is compared to the spectra obtained by combining the data of 3 and 5 June and the combined data for 3, 4, and 5 June.

signal consisted of the radar echo in the center three channels (Fig. 1) plus the thermal emission from Titan and the system noise in all channels. The fundamental problem of our experiment is to detect the presence of the echo in the three center channels, particularly the central channel. Information on the echo detection is contained in both the amplitude spectrum and the phase spectrum. The phase of the noise is uniformly distributed between ±180 degrees. If there is a point source in the fringe, such as Titan, the phase of the signal part of the measured output will be zero if the ephemeris is perfect. This is essentially the case for Titan with the fringe spacings that we used. Thus in the limit of very large signal-to-noise ratio, the measured visibility vectors would have phases very near zero and amplitudes very near the true signal strength (*15*).

The statistics of our signals are slightly complicated by the presence of the thermal emission from Titan of about 3 mJy in all channels, to be compared with the rms noise of about 7 mJy in each channel for a day's integration of about 4.5 hours. The presence of this small signal from Titan biases the output phases slightly toward zero even in the channels that do not contain radar echo energy. We have devised a test for the detection of a radar signal and a quantity called the detection measure (DM). Given that we measure an amplitude A_0 and a phase ϕ_0 in a radar channel, we ask the question: what is the chance that A_0 and ϕ_0 arose from random noise alone plus the 3 mJy continuum emission, that is, a random complex number from the tail of the bivariate distribution? We computed the detection measure with a Monte Carlo noise calculation of the number of trials (out of 10,000) in which the amplitudes exceeded A_0 and the absolute value of the phases was less than ϕ_0. The reciprocal of this fraction is the detection measure. We do not include the fact that the signal happens to be in the radar channel, that is, the fact that the large amplitude and small phase are in the central channel. The calculated detection measures for the radar channels for the three separate days, the sum of the data for 3 and 5 June and the sum of the data for all three days are shown in Table 2. The symbol ∞ in this table means that there were no trials in the 10,000 that met the criterion. Very large values of the DM mean that the observed amplitude and phase were not a consequence of random fluctuations and a case with ∞ is virtually certain to be a true echo from Titan. The data for the central channel for all three days strongly argue for the detection of the radar echoes although the detection measure of 25 for channel 0 on 3 June is relatively weak,

Table 2. Detection measures (DM).

Date	Channel	Amplitude (mJy)	Phase (degrees)	DM
3 June	−1	20.6 ± 7.7	101	20
	0	22.1 ± 7.7	58	25
	+1	10.4 ± 7.7	51	5
4 June	−1	16.9 ± 8.2	−7	80
	0	33.7 ± 8.2	−9	∞
	+1	29.5 ± 8.2	15	2000
5 June	−1	14.7 ± 7.9	−4	125
	0	17.0 ± 7.9	5	142
	+1	2.4 ± 7.9	−122	~1
3 + 5 June	−1	10.6 ± 5.9	61	9
	0	17.6 ± 5.9	36	128
	+1	4.0 ± 5.9	49	3
3 + 4 + 5 June	−3	1.5 ± 4.3	86	1.4
	−2	6.0 ± 4.3	−104	3
	−1	10.6 ± 4.3	31	29
	0	21.2 ± 4.3	13	∞
	+1	12.0 ± 4.3	22	111
	+2	6.0 ± 4.3	−52	4
	+3	4.8 ± 4.3	−32	4

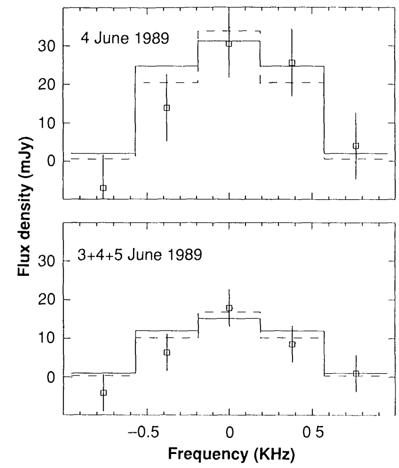

Fig. 4. The observed amplitude spectra for 4 June and the combined data are indicated by the squares. The continuum flux density of 2.8 mJy has been subtracted. The lines show least-squares fits to these data for radar backscatter laws of the form $\cos^1(\theta)$, solid lines; $\cos^2(\theta)$, dashed lines; and $\cos^3(\theta)$, dotted lines. Only the three central channels can contain radar echo energy.

suggesting that there is a 4% chance it could be just noise. Thus, there are some doubts about the detection for 3 June if we use a 96% confidence interval. The detection measures for 4 June strongly support the presence of radar energy in all three channels. The same is true for the average of all three days. The results when the 4 June data are excluded, while supporting the radar signal in the central channel, are equivocal about the presence of a broad radar echo. We conclude from Table 2 that the radar echo was detected on all three days and that significant energy was reflected over the entire disk, at least on 4 June, to indicate that the backscatter process is not specular like that from a terrestrial planet, but is more diffuse like the echoes from the Galilean satellites. Values of DM for other than the center three channels are completely consistent with statistical expectations. The DM for four channels which cannot contain radar echo energy are presented in Table 2 for the sum of the 3 days. Of course, pathological cases can be found by searching the spectra for them. The chance that one would fall in the center channel is 1/64.

We can learn something about the surface structure by analyzing the spectral shape. Calibrated spectra for 4 June and for the vector average of all three days are shown in Fig. 4. Models that we fit to the observations are indicated by the straight lines which represent the response of each 381-Hz channel. If Titan were a diffuse reflector with power scattered equally into 2π steradians from each surface element, the backscattering law would be proportional to the cosine of the incidence angle. That case is shown by the solid lines in Fig. 4. Slightly more directed backscatter spectra are indicated by the dashed and dotted lines for cosine squared and cosine cubed laws, respectively. While the data favor the cosine squared curve, all are good fits. We conclude that the backscatter from Titan is highly diffuse, similar to that of Europa, Ganymede, and Callisto. This is a strong argument against an ethane ocean being the reflecting medium since a liquid body (without floating scatterers) would be a specular reflector except for the rather pathological case of waves, which would tend to create a sum of specular reflectors over a range of incidence angles. However, the diffuse spectra are not very consistent with the variations in the echo strengths over the three consecutive days. If the scattering mechanism is highly diffuse, echo power will be received from most of the visible hemisphere and small daily variations are expected for a slow rotator. We cannot resolve this paradox with the available data but it seems possible that the relatively large noise in the amplitude spectra is confusing us. It is clear, however, that the region on the sub-Earth point on 4 June is a much stronger backscatterer than that for the other 2 days.

Strong radar echoes were obviously obtained on 4 June and the detection on 5 June is also quite certain. We tested the hypothesis that the observed echoes in the central channel of all three days are consistent with a constant value of reflectivity plus the data noise. We adopted as the "best value" the amplitude from the spectrum for the combined 3 days, 21.2 mJy from Table 2 and 0 phase. Another Monte Carlo computation was performed to determine whether the observed amplitudes and phases for the separate days are consistent with the hypothesis. The results are probabilities of 0.04 for 3 June, 0.27 for 4 June, and 0.86 for 5 June. We conclude from this exercise that the weakness of the echo on the first day (manifested by its large phase) is not consistent with a homogeneous surface and that the strong reflection on the middle day is somewhat consistent with the mean and with the third day. The data appear to favor a real variation in surface properties but more observations are required.

Total Reflectivity

The total reflectivity or the radar cross section for the polarization configuration used in this experiment can be obtained by integrating the amplitude spectrum. The ratio of this power to that of an equivalent smooth conducting sphere of Titan's radius is the cross section for the polarized echo. These results are shown in Table 3 (*16*). The average cross section for the entire experiment is 0.35 ± 0.08 for the region sampled. The error on this estimate is 1 standard deviation computed from the integration of the noise over three channels for the combined, raw data set. The cross section on 4 June is 0.78 ± 0.15. These high reflectivities could be achieved from a surface with dielectric constants greater than 10 but such surfaces would be grossly inconsistent with the thermal brightness temperatures discussed below (*6*). It can be seen that the daily variation is clearly present. A comparison of these results with the values in Table 1 show that Titan behaves differently from simple dielectric surfaces and the terrestrial planets and that a deep liquid ethane medium can be nearly ruled out for the part of the satellite studied here. The question of shallow oceans must be addressed although we are somewhat limited by a lack of information on the microwave absorption coefficients for liquid hydrocarbons. The real part of the dielectric constants is well known to be in the range from about 1.6 to 1.8 (*17*). We know of no direct measurements of the imaginary part nor of sufficiently accurate measurements of the real part over a frequency range which will allow the computation of the absorption coefficients from the dispersion relationships. Loss tangents on the order of 10^{-4} are typical for other nonpolar hydrocarbons (*17*). Furthermore, one can only guess at the homogeneity of such liquids on Titan but we cannot think of any matter that would float in such a liquid and act as efficient scatterers. We have modeled the normal incidence reflection coefficient for a layer of a complex dielectric over a reflecting substrate with a slightly variable interface depth (*18*). The variable depth removes the resonances in the standing waves which would certainly not occur in nature. We find that the effect of the reflecting layer is reduced to about 1% for liquid depths of about 35 m and 150 m for loss tangents of 10^{-5} and 10^{-6}, respectively. That is, at greater depths than these, the medium appears homogeneous and has the reflecting properties of liquid ethane shown in Table 1 which are different from those of Table 3. Thus, if the oceans are shallower than these values, we would detect the properties of the substrate. However, we cannot imagine a specific substrate flooded with a liquid which would exhibit the observed reflection and emission properties. The problem remains that there must be a source for CH_4 which is continually destroyed by photochemical processes with a subsequent loss of atomic hydrogen. A solid ice subsurface would have insufficient reflectivity, and a highly reflecting surface due, for example, to some combination of organic compounds, would have insufficient emissivity.

Table 3. Total echo power and radar cross sections. Uncertainties do not include that of VLA collecting area, which cancels in the cross section determination.

Date	Observed power (W)	Reference sphere (W)	Cross section
3 June	$(1.09 \pm 0.42) \times 10^{-21}$	2.88×10^{-21}	0.38 ± 0.15
4 June	$(2.09 \pm 0.41) \times 10^{-21}$	2.69×10^{-21}	0.78 ± 0.15
5 June	$(0.70 \pm 0.40) \times 10^{-21}$	2.81×10^{-21}	0.25 ± 0.15
3 + 4 + 5 June	$(0.99 \pm 0.22) \times 10^{-21}$	2.79×10^{-21}	0.35 ± 0.08

We believe that the most likely explanation of our observations is that the reflecting medium is similar to the surfaces of Europa, Ganymede, and Callisto. Their radar cross sections are (*10*) 0.40 ± 0.06 for Ganymede at a wavelength of 3.5 cm and 1.1 ± 0.25 (Europa), 0.61 ± 0.15 (Ganymede), and 0.25 ± 0.05 (Callisto) at a wavelength of 12.5 cm. Although the physics of the reflections from the Galilean satellites remains a puzzle, it is clear that subsurface scattering from interface cracks or volume scatterers in very cold (that is, transparent) ice is the central idea (*10*). Furthermore, it appears reasonable that this very strong backscattering phenomena would be quenched if the medium were flooded with a liquid with a dielectric constant ϵ very near to that of the solid ice. Goldstein and Green (*10*) showed that multiple reflections in ice with $\epsilon = 3.0$ with cracks containing a vacuum could explain the Ganymede cross section. If the cracks on Titan were filled with ethane, the dielectric constant would be reduced to $3.0/1.8 = 1.67$, greatly reducing the effect. That is, the medium would act as if it were more homogeneous, greatly reducing the cross section toward that of solid ice or about 7%. Thus, it appears that the radar echoes from Titan are coming from a near-surface matrix "resembling" that of the Galilean satellites. It is likely that the near surface has a component of solid hydrocarbons but we feel that it is unlikely that the reflecting layer is beneath a shallow sea. An additional interesting argument against the existence of shallow seas was presented by Sagan and Dermott (*19*). These authors argued that tidal friction in *shallow* seas would have very quickly reduced the eccentricity of Titan's orbit to zero.

The results of this experiment in no way rule out the existence of liquid hydrocarbons on Titan's surface in the form of small lakes. Such structures would merely reduce the average measured cross sections.

Brightness Temperatures

Measurements of the surface brightness temperatures of Titan also contain information about the surface (*6*). At wavelengths longer than 1 cm the atmosphere is sufficiently transparent such that the measurements are dominated by the surface properties, primarily the surface emissivity. The available measurements are listed in Table 4 including estimates from this work using the 145 KHz broadband channel and the averages over the narrowband spectral channels. Since the system noise is proportional to the inverse square root of the bandwidth, our new values are of limited use. The 2.67-mm measurement is low because the absorption by molecular nitrogen in the cold Titan atmosphere is important. Nitrogen absorption is of some importance for all the measurements. The weighted mean brightness temperature for the centimeter measurements is 83.8 ± 6.4 K. A model calculation (*20*), including the small effects of the atmosphere, yields a brightness temperature of 85.6 K for a

Table 4. Thermal emission brightness temperatures of Titan, assuming radius of 2575 km.

Wave-length (cm)	Bandwidth (MHz)	Brightness temperature (K)	References
0.267	300	69 ± 10	Muhleman *et al.* (*6*)
2.0	50	76 ± 5	Muhleman *et al.* (*6*)
2.0	2 × 50	86.4 ± 3.7	Wagener *et al.* (*6*)
3.5	0.145	86 ± 17	This paper
3.5	0.023	112 ± 18	This paper
6.0	50	82 ± 9	Muhleman *et al.* (*6*)

surface with a dielectric constant of 2.0, 81.7 K for a dielectric of 3.0, and 87.0 K for an ethane sphere, all of which are consistent with the measurement. The thermal emission measurements are consistent with a lunar-like surface but not with a Ganymede-like surface. Brightness temperature measurements of Europa and Ganymede (*21*) are depressed by 40 to 50% which is roughly consistent with their high radar reflectivities and the standard reciprocity relationship between reflectivity and emissivity (*22*).

We are left with a quandary. The radar experiment shows that the Titan surface is a strong backscatterer of 3.5-cm waves. Microwave thermal emission measurements and modeling indicate that the surface is a relatively good emitter at similar wavelengths. If both of these observations are correct, they pose a dilemma. A large dielectric constant helps to explain the radar cross sections (but not the diffuse reflection) and a low dielectric constant explains the emission. However, radar reflection is dominated by the details of the near-surface structure such as roughness, to which the emission is quite insensitive. Apparently, the surface of Titan has a very high backscatter gain or directivity which has little effect on the emission. That is not the case for the Galilean satellites where the high reflectivities are associated with low emissivities at centimeter wavelengths.

Future Prospects

The VLA/JPL radar measurements will be repeated as often as possible during the closest passages of Titan to the Earth. Both circular polarization modes can be measured. Significant increases in the transmitter power are scheduled for the 70-m antenna. However, most of the questions concerning the Titan surface will not be answered until the proposed Cassini spacecraft reaches the Saturn system. Repeated close flybys of Titan offer the opportunity to map the microwave emission brightness temperatures and the microwave polarization yielding maps of the effective dielectric constants which can be interpreted in terms of surface coverage of hydrocarbon lakes and solid terrains. It is quite likely that such a spacecraft would have an imaging radar and altimeter which will reveal much of the surface structure and will be very important for the study of Titan's geology but will not be able to measure the surface reflectivity with an accuracy near to that of even current Earth-based radars.

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7. R. Goldstein *et al.* (1987), in an unpublished manuscript found a statistically significant peak in their 3.5-cm wavelength radar spectrum 70 Hz off the correct frequency. A repeat of their experiment gave a negative result in 1988.
8. The 70-m antenna at Goldstone, CA, is part of the NASA Deep Space Network operated by the Jet Propulsion Laboratory. The Very Large Array near Socorro, NM, was built by the National Radio Astronomy Observatory and is operated by Associated Universities, Inc., under contract with the National Science Foundation.
9. The radar transmitter consists of the NASA/JPL Goldstone 70-m antenna and a 360,000 (±5%)-W, 8.495-GHz continuous wave transmitter operating in the right circular polarization (RCP) mode. The effective area of the antenna is 2616 m^2 (±3%) at a 29-degree elevation angle. The receiving instrument was the NRAO Very Large Array in New Mexico consisting of 27 antennas (diameter 25 m) with an effective collecting area of 7952 m^2 (±5%). The signals were received in 63 spectral channels with resolution = 381 Hz in the left circular polarization (LCP) mode. The mean distance to Titan was 9.317 AU and the total Doppler spread of the radar echo signals are expected to be ~1200 Hz assuming that Titan rotates synchronously with its orbital motion around Saturn (15.9 days). The VLA receivers' system temperatures were ~35 K and the mutual visibility between Goldstone and the VLA was ~5 hours.
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12. Measurements made on the 70-m radar cone by G. W. Garrison (*Internal Memorandum IOM 3300-88-525*) (Jet Propulsion Laboratory, Pasadena, CA, 1988). The pointing of the transmit beam has been qualitatively verified by VLA/Goldstone maps of Mars by the authors. However, for a radar source such as Titan it is difficult for the experimenters to directly test the pointing and the focusing of the transmitter beam. We regard it highly unlikely but possible that the weak signals on 3 June and 5 June are due to such effects. The VLA pointing is experimentally verified during the experiment by monitoring the thermal emission from Titan which is present in all spectral channels.
13. The flux density of P1908-201 was measured relative to the standard 3C286 (5.16 Jy) and the calibration is believed to be accurate to 5%.
14. The CLEAN software package at the VLA is a beam deconvolution algorithm that is used to replace an observed map by an equivalent map of point sources which would reproduce the observations, including sidelobes.
15. False images of a pseudopoint source at the center of VLA maps are occasionally seen in the broadband continuum mode due to signal leakage. No such false images have been seen in the spectral line observing mode in several years because the leakage is very small relative to the noise in a narrow spectral channel.
16. The amplitude of the signal was computed from the biased amplitude plus noise with the formula $\sqrt{(\text{amplitude})^2 - (\text{rms noise})^2}$, see A. Thompson *et al.*, *Interferometry and Synthesis in Radio Astronomy* (Wiley, New York, 1986), p. 262. The radar signal was then corrected for the continuum emission estimated from the mean of the real part of the spectrum excluding the three central channels.
17. See, for example, S. Singh and R. Miller, *J. Chem. Thermodynamics* **11**, 395 (1979) and references cited therein. G. Reesor, *Canadian J. Phys.* **53**, 2611, unpublished work of V. Anicich (JPL).
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20. Three-dimensional model of the atmosphere and surface of Titan and the associated radiative transfer was developed by R. T. Clancy and D. Muhleman.
21. D. Muhleman, G. Berge, D. Rudy, *Icarus*, in press; see also I. de Pater, R. Brown, J. Dickel, *ibid.* **57**, 93 (1984).
22. The reflection coefficient at normal incidence of a band of radiation from a "smooth" gray surface is equal to (1 − emission coefficient for the same band). However, the reflection coefficient of monochromatic radiation from a rough surface may be dominated by scattering phenomena which may be strongly different from the scattering effects in the emission of broadband thermal radiation. Thus, the measured values of the radar reflectivity are weakly related to the emissivity for many surfaces.

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