below those chemically maintained by A horizon soils in laboratory equilibrations, an indication of regulation through biological uptake. Using computer-based estimates of hydrologic flow across the A horizon–B horizon interface (*7, 14*) and assuming that the phosphorus contents of these solutions did not vary seasonally, we calculated that 0.23 kg per hectare of total phosphorus leach from the A horizons to the B horizons annually. This amount is only 3 percent of the 8.35 kg ha^{-1} $year^{-1}$ estimated to be released within the A horizons (*15*), and it indicates strict biological retention of phosphorus within surface soils. Solutions collected from lysimeters placed in the middle of the B2ir invariably contained ≤ 1 μg of total phosphorus per liter, substantiating the hypothesis of geochemical control of dissolved inorganic and organic phosphorus in subsoils and eventually stream waters.

Our results indicate dual and stratified regulation of phosphorus cycling and retention at Hubbard Brook. Phosphorus is biologically conserved within this forest community by close coupling of biological decomposition and uptake processes in the surface soils. Underlying iron- and aluminum-rich B horizons, in turn, function as massive geochemical buffers that regulate the constant and low-level losses of dissolved phosphorus with stream water.

These findings are significant in explaining changes in phosphorus biogeochemistry after forest disturbance. Experiments at Hubbard Brook have demonstrated massive increases in stream water exports of calcium, potassium, and nitrate-nitrogen after clear-cutting. Losses were attributed to disruption of biological retention mechanisms as well as to acidification of cation-exchange sites in the profile (*6, 16*). Stream water losses of dissolved inorganic phosphorus did not increase after clear-cutting (*17*), presumably because chemical processes in the B horizons continued to function. With disruption of biological controls in surface horizons, however, it is likely that large amounts of phosphorus migrated from the forest floor to sinks in the B horizons. Recovery of phosphorus stored in those subsoils may represent an important aspect of forest regrowth after disturbance.

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8 August 1983; accepted 1 November 1983

Microwave Measurements of Carbon Monoxide on Titan

Abstract. *The ratio of the flux density of Titan was measured in two 200-megahertz bands, one centered on the (1–0) rotation line of carbon monoxide at 115.3 gigahertz and the other 2600 megahertz lower. The measurements were made with a complex-correlation technique on the new millimeter-wavelength interferometer at the Owens Valley Radio Observatory, Big Pine, California. The excess flux in the carbon monoxide band is interpreted as a strong detection of carbon monoxide and a mixing ratio, assumed constant, of* 6×10^{-5}. *The brightness temperature of Titan at 112.6 gigahertz is 69 ± 10 kelvins, consistent with atmospheric emission from just below the tropopause.*

Until recently, the known constituents of the Titan atmosphere were CH_4, C_2H_6, C_2H_2, and CH_3D. Experiments on Voyager during its flyby of Titan established that N_2 was the primary constituent, with no more than 3 percent CH_4 (*1*). Numerous other species were detected, all of which could be products of the parent compounds N_2 and CH_4. We began a series of measurements in early 1982 to detect the first rotational transition of CO at 115.271 GHz, since that line is very strong in the terrestrial planets and the detection of an oxygen compound in Titan would be extremely important (*2*). Concurrently, Samuelson *et al.* (*3*) interpreted an emission feature in the Infrared Interferometer Spectrometer (IRIS) spectrum at 667 cm^{-1} as CO_2, and recently prepared a paper in which they predicted a constant CO mixing ratio of 1.1×10^{-4} based on their photochemical model and a CO_2 mixing ratio of 1.5×10^{-9}. In their model the CO/CO_2 ratio is very large because of the low abundance of H_2O, which is an important source of OH, a critical molecule in the conversion of CO into CO_2. Lutz *et al.* (*2*) detected CO in Titan with Earth-based measurements in the (3–0) rotational-vibration bands near 6350 cm^{-1} and interpreted their measurement with a constant mixing ratio of 6×10^{-5} with an uncertainty of a factor of 3. This uncertainty arises from a multitude of causes, including the possible presence of aerosol, cloud, and haze layers in Titan's atmosphere, which would seriously influence their interpretations. The microwave lines offer a more direct means of measuring the abundance, since the emission is only affected by gaseous absorption and confusion from other chemical species is very unlikely. Any liquid droplets in clouds would probably be nonpolar and, consequently, would not be significant absorbers. The primary problem is one of signal-to-noise ratio.

Titan was observed on 7 and 8 May 1983 by use of the millimeter-wavelength, two-element interferometer at the Owens Valley Radio Observatory, Big Pine, California. The interferometer consisted of two 10.4-m telescopes (*4*) positioned to give a baseline of 50 m east-west. At a nominal wavelength of 2.6 mm the fringe spacings on the sky in the direction toward the Saturn system ranged from about 10.6 to 21.4 arc seconds. The interferometer fringes were continuously positioned on Titan with computer-controlled phase tracking, using a precise Titan ephemeris (*5*). During

Table 1. Flux density, brightness temperature, and ratio measurements.

Date or measurement	Source	Amplitude	Phase (degrees)	Side-band
1. 7 May 1983	Titan/P1334-127	0.151 ± 0.028	12 ± 10	Upper
2. 7 May 1983	Titan/P1334-127	0.081 ± 0.030	16 ± 15	Lower
3. 8 May 1983	Titan/P1334-127	0.136 ± 0.030	−9 ± 11	Upper
4. 8 May 1983	Titan/P1334-127	0.106 ± 0.019	7 ± 6	Lower
5. Weighted vector average	Titan/P1334-127	0.142 ± 0.010	2 ± 8	Upper
6. Weighted vector average	Titan/P1334-127	0.096 ± 0.012	8 ± 2.4	Lower

7. Flux ratio, $\mathrm{Titan_{USB}/Titan_{LSB}} = 1.48 \pm 0.19$
8. Brightness temperature in CO line* = 105 ± 14 K

*Assuming $T_B = 74.5$ K at $\lambda = 2.661$ mm and the Rayleigh-Jeans approximation.

the observations the center of the Saturn system was never closer than 240 arc seconds from Titan and the planet was moving rapidly through the fringes. Consequently, no confusion from Saturn is evident in the data, although it must be present as a small, nearly random, noise source.

The instrument, with a superconductor-insulator-superconductor (SIS) (*6*) superheterodyne receiver on each telescope, had a double-sideband response with a band separation of about 2600 MHz and a nominal width of 200 MHz for each sideband. The frequency was set such that the (1–0) rotational transition line of CO was held in the center of the upper sideband (USB). Thus, the lower sideband (LSB) was roughly 2.6 GHz below the line center. The Titan Doppler shift was removed by continuously adjusting the phase-coherent local oscillators according to the ephemeris. The signals from the two telescopes were multiplied and detected in a complex correlator, which allowed for the separation of USB and LSB fringes; that is, there were separate fringes from the two independent parts of the spectrum, although part of the system noise remained correlated.

At approximately half-hour intervals a quasi-stellar source (QSS), P1334-127, was observed as a phase and amplitude calibrator. A single measurement consisted of a 3-minute scan in which the fringe amplitude (uncalibrated flux density) and fringe phase were recorded. During data reduction, the instrumental phase curve was obtained from the calibrator and subtracted from the Titan phases, scan by scan. Similarly, a smooth curve was generated from the calibrator amplitudes. This curve was used to compute the ratio of the flux density of Titan to that of the calibrator. Since the calibrator was within 6.4 degrees of Titan, this procedure removed the atmospheric absorption function from the data after a small correction of the slight differences in zenith angles. Thus, the fundamental measurements of this experiment are two (USB and LSB) nearly independent ratios of the Titan-to-calibrator flux densities and the fringe phases of Titan relative to the calibrator.

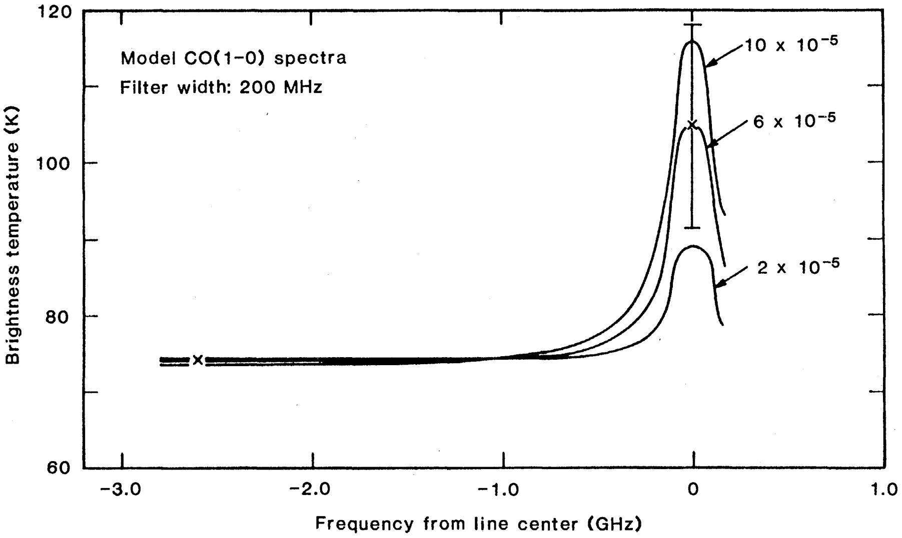

Fig. 1. Microwave emission spectra of the CO (1–0) line (115.271 GHz) convolved with a 200-MHz bandpass function for three values of the CO/N_2 mixing ratio; (x) LSB and USB temperatures computed from the measured flux density ratio. The lower point was fixed to the model value and the upper computed from the ratio, including its error.

The latter are proportional to the instantaneous component of the Titan calibrator ephemeris error in the plane of the fringes (plus noise).

The measurements in each sideband were vector-averaged over each day's pass (8 hours) and are shown in the first four rows of Table 1. On both days the USB flux ratio containing the effects of CO emission from Titan is significantly larger than the LSB ratio. The estimated phases are small; for instance, 10 degrees of phase corresponds to 10/360 of a fringe or about 0.3 arc second, which is consistent with our expected ephemeris error and the error in the position of P1334-127.

Rows 5 and 6 in Table 1 show the weighted vector averages for the 2 days. The ratio of the upper and lower sideband amplitudes of 1.48 ± 0.19 is given in row 7. This ratio can be interpreted as the ratio of flux density of Titan in the 200-MHz band containing the CO emission line to the band 2.6 GHz from the line center if the flux density of P1334-127 is constant in the range 112.7 to 115.3 GHz. It is highly unlikely that the flux density of the QSS could vary in frequency by an amount significant enough to affect our measurements and interpretations. Thus, we feel that row 7 of Table 1 represents an essentially self-calibrated flux ratio in and out of the CO line and that there is relatively strong CO emission from Titan. It is possible that another molecule in our upper sideband is the source of the extra flux, but no such molecular species with a significant dipole moment occurred to us when we considered the known and likely chemistry of Titan's atmosphere. The list of molecules we eliminated includes N_2, CH_4, H_2, HCN, H_2O, CO_2, C_NH_M, and others. Row 8 of Table 1 is discussed below.

Interpretation of sideband flux ratio. The quantitative interpretation of our measured ratio of the Titan flux density in and out of the CO line requires a radiative transfer calculation for a model of the surface and atmosphere of Titan. The temperature-pressure profile was accurately measured during the radio occultation of Voyager 1 by Titan. The profile we used is that given by Lindal *et al.* (*1*), where a pure N_2 atmosphere was assumed for the interpretation of the Voyager occultation refractivity measurements. The possible deviation from pure N_2 of a few percent of CH_4 will not significantly affect the interpretation of microwave measurements at wavelengths longward of 1 mm. Following the suggestion of Thompson and Sagan (*7*), we included collision-induced absorption in N_2 as a microwave opacity source along with the pressure-broadened resonant absorption from CO. Laboratory measurements by Ho *et al.* (*8*) of absorption by pure N_2 yield a microwave absorption coefficient

$$k_\lambda = \frac{1.07\,P^2}{\lambda^2}\left(\frac{273}{T}\right)^{4.5} \times 10^{-9}\ \mathrm{cm}^{-1} \quad (1)$$

where the pressure (P) is in atmospheres and the wavelength (λ) is in centimeters. The measured temperature (T) dependence was difficult to interpret theoretically (*8*) and is of some concern to us. Our model predicts a signal transmission of 0.3 for a grazing occultation ray at X-band. This is a factor of 2 less than the limiting transmission reported by Lindal *et al.* (*1*) for the Voyager X-band occultation. However, it is clear that the N_2 absorption at 2.6 mm is sufficiently strong below the tropopause on Titan that essentially all of the continuum flux that we detected in both sidebands was generated just below that point. We assume that the CO is uniformly mixed in the atmosphere from the surface through the stratosphere, consistent with photochemical models (*3*). Our determination of the CO mixing ratio is quite insensitive to the exact N_2 absorption coefficient; for example, the estimated mixing ratio is only doubled if we completely ignore N_2 absorption. This is because most of the CO resonant emission in our bandpass is generated above the tropopause and the N_2 absorption primarily affects the continuum blackbody emission from the lower atmosphere and surface, which has relatively little effect on our measured ratio.

We modeled the surface as smooth dielectric sphere with a dielectric constant of 2, 3, or 4. Nonpolar liquids such as N_2, CH_4, and many organic compounds have dielectric constants of 2 or slightly less. The ices of H_2O, CO_2, CH_4, and so on tend to have values near 3, while compact soils tend to have values between 3 and 4. These considerations are important for an understanding of the entire microwave spectrum discussed below but are unimportant for our 2.6-mm measurements, since the CO-N_2 opacity does not allow surface emission to reach us.

The radiative transfer model consists of 16 horizontally stratified atmospheric layers over the dielectric surface at temperature 94 K. The opacity sources are the resonant CO (1–0) absorption coefficient with the Van Vleck–Weisskopf pressure-broadened line shape function and the N_2 absorption coefficient, Eq. 1. For a given constant CO mixing ratio the brightness temperature as a function of frequency was computed at 25-MHz intervals and convolved over 200 MHz, corresponding to each of our sidebands. The resulting brightness temperature spectra for three values of the mixing ratio are shown in Fig. 1. After converting our measured flux density ratio to a brightness temperature (T_B) ratio by using the Rayleigh-Jeans approximation, we computed the brightness temperature in the CO band (USB) by adopting the model temperature for the LSB of 74.5 K. The measured temperature ratio times this value is 105 ± 14 K, as shown by the crosses in Fig. 1 and row 8 of Table 1. In this way we estimate that the CO mixing ratio is between 2.3×10^{-5} and 10.2×10^{-5}, with the most probable value 6×10^{-5}.

Most of the error in our estimate of the CO mixing ratio is measurement error caused by the weakness of the Titan signals. Most systematic errors have been removed by the self-calibration nature of the experiment. The largest remaining error is probably the uncertainty of the N_2 absorption coefficient after extrapolation to the cold temperature of the lower atmosphere of Titan. We repeated the calculations with half the value of the N_2 absorption coefficient, which resulted in an increase in the mixing ratio for the best fit by 3 percent.

Table 2. Absolute Titan measurements.

Date	Source	Flux density (Jy)	
		LSB, λ = 2.661 mm	USB, λ = 2.601 mm
4 May 1983	P1334-127	3.46 ± 0.11	3.19 ± 0.21
9 May 1983	P1334-127	3.23 ± 0.12	2.97 ± 0.21
Weighted mean	P1334-127	3.35 ± 0.11	3.08 ± 0.21
Weighted mean	Titan	T_B (LSB)* = 69.0 ± 10 K	T_B (USB)* = 90 ± 16 K

*Assuming a Titan radius of 2575 km.

Absolute brightness temperatures. On 4 and 9 May 1983 we observed Saturn plus rings with respect to the QSS P1334-127 in an attempt to determine the absolute flux density of the quasar and, therefore, that of Titan. The interferometer strongly resolved the Saturn disk and ring system and careful modeling of the system was required in order to determine the quasar's flux density (*9*). We adopted a value of 150 ± 5 K for the 2.6-mm brightness temperature of the Saturn disk and 10 K for the rings. Saturn data from the upper and lower sidebands were treated as independent data sets in this calculation. Since the zenith optical depth of the earth's atmosphere is about 0.2 unit greater in the USB due to the terrestrial O_2 line centered at 118.7 GHz, the USB data are much noisier. Furthermore, the CO abundance, if any, in the

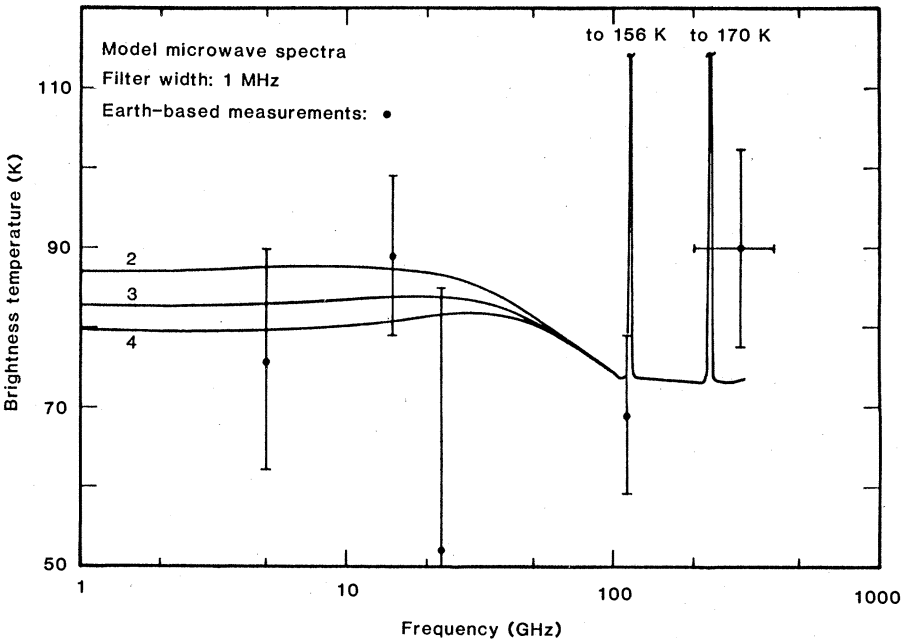

Fig. 2. Entire microwave spectra of Titan for three values of the surface dielectric constant with the published measurements. The value at 113 GHz is from this work. The lowest two CO resonance lines for our CO mixing ratio are shown, assuming a 1-MHz filter width.

atmosphere of Saturn is an open question which is being examined separately. Thus, the measurements in the LSB are much more reliable than those in the USB. The results for P1334-127 are shown in the first three rows of Table 2 and the best estimate of the flux density at $\lambda = 2.661$ mm is 3.35 ± 0.11 jansky. The resulting "continuum" brightness temperature of Titan is 69.0 ± 10 K. Results for the USB are shown for completeness. Clearly, the ratio of the two Titan temperatures from Table 2 is far less accurate than that from Table 1.

We show the entire microwave spectral models of Titan for three surface dielectrics in Fig. 2. Also shown are our measurement at 112.6 GHz, the three Very Large Array (VLA) measurements of Jaffe *et al.* (*10*) at 5, 15, and 23 GHz, and the 1-mm bolometer measurement from Roellig *et al.* (*11*). The last measurement was corrected from the published value of 86 ± 12 K to 90 ± 12.5 K, using an effective radius at 1 mm of 2650 km computed from our model. This measurement included the (2–1) CO emission line in the instrument bandpass. We estimate a +3 K contribution to the measured brightness temperature with our value of the CO mixing ratio. The effect of the surface dielectric constants of 2 (nonpolar liquids), 3 (ices), and 4 (compacted soils and rock) are evident below 80 GHz. The current VLA measurements are not accurate enough to distinguish the surface effects. Future measurements at the VLA should have an accuracy as good as ±5 percent or ±4 K.

Conclusions. The Titan emission line for the lowest rotational transition of CO (115.3 GHz) has been measured. Assuming constant mixing of CO for the entire atmosphere, we estimate a mole fraction of 6×10^{-5}, in excellent agreement with Lutz *et al.* (*2*). This is a factor of 2 smaller than the value predicted by Samuelson *et al.* (*3*), based on their interpretation of the 667-cm^{-1} CO_2 emission line in the Voyager 1 IRIS spectrum and photochemical modeling.

Collision-induced absorption due to N_2-N_2 interactions causes the atmosphere to be opaque at 2.6 mm somewhat below the tropopause. The microwave CO line is formed in the relatively hot atmosphere above this level. Models of the complete microwave spectrum must be regarded as tentative until laboratory measurements of the N_2 collision-induced absorption coefficient at the relevant Titan temperatures and pressures are carried out. Nevertheless, it is apparent that careful measurements in the frequency range 5 to 80 GHz could resolve the question of a liquid surface (*12*). High-resolution VLA measurements may be sufficiently accurate to directly yield the polarization of the surface emission, from which the dielectric constant can be estimated. Future spacecraft microwave measurements to an accuracy of about ±1 K will ultimately be important in resolving the Titan surface structure.

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29 August 1983; accepted 5 October 1983

Thickness of Saturn's Rings Inferred from Voyager 1 Observations of Microwave Scatter

Abstract. *Earth-based telescopic observations indicate that Saturn's rings are about 1 kilometer thick, while spacecraft measurements and theoretical considerations give an upper bound of about 100 meters. Analysis of a shielding effect present in radio occultation provides a sensitive new measure of the ring thickness. On the basis of this effect, Voyager 1 microwave measurements of near-forward scatter imply a thickness ranging from less than 10 meters in ring C to about 20 and 50 meters in the Cassini division and ring A, respectively. Monolayer models do not fit the observations in the latter two regions. The discrepancy between the Earth-based and spacecraft measurements may be due to warps in the ring plane or effects of tenuous material outside the primary ring system.*

The thickness of Saturn's rings as observed from Earth is estimated to be about 1 km (*1*). Voyager spacecraft observations of edges in the ring system give upper bounds to the thickness of 100 to 200 m (*2*). Estimates based on the observation of density wave phenomena in the rings and theoretical considerations give values of 10 to 50 m (*3*).

We present new evidence from microwave scatter in the near-forward direction indicating that the rings are, at most, a few tens of meters thick and, with the possible exception of ring C, are dispersed vertically so that they are thicker than an ideal monolayer of particles. These results, which apply to several broad areas in rings A and C and the Cassini division, are independent of dynamical modeling. No results for ring B are available since the combination of large radio depth and a small ring opening precluded observation of microwave scattering from that region.

The data were obtained during the occultation of Voyager 1 by the rings when radio transmissions from the spacecraft passed through the rings to be received on Earth (*4*). These data have been reduced to the differential scattering cross section $\sigma_d(\alpha)$ (square meter per square meter per steradian) of 3.6-cm-wavelength (λ) radiation over the range $0 \leq \alpha \leq 0.012$ rad, where α is the scattering angle (*5–7*). These cross sections have been obtained for eight locations in the ring. Simultaneous measurement of the unscattered, or "direct," signal ex-