Absorption of Radar Signals by the Atmosphere of Venus

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ABSTRACT

Attempts to study the radiowave reflection properties of Venus by radar at 3.8 cm wavelength are reviewed. Measurements made by the Lincoln Laboratory during the last three inferior conjunctions place the scattering cross section at 1.7% of the projected area of the planetary disk. At 12.5 cm wavelength, a cross section of 11.5% has been reported and at wavelengths of 23 cm or longer the cross section appears to be ≥15%. No comparable wavelength dependence is found in the radar cross sections of the moon, Mercury or Mars, and it is believed that in the case of Venus, absorption of the waves by the atmosphere is responsible for the low cross section observed at the shortest wavelength.

Support for this conclusion has been obtained by comparing the scattering behavior observed at 3.8 and 12.5 cm. For Venus the reflectivity of the limbs compared to that of the disk center is lower at 3.8 cm than at 12.5 cm wavelength, while in the case of the moon the reverse is true. If the additional limb darkening is attributed to the attenuation of the rays that pass through the atmosphere obliquely, the difference in the two-way absorption can be established as 5±1 db. The radar cross section observed at 3.8 cm is lower than that at 12.5 cm by 8±3 db. Thus, it appears that the one-way absorption of 3.8 cm microwaves by the atmosphere of Venus is at least 2.5 db and possibly more. This is significantly greater than can be accounted for by an atmosphere consisting of CO_2 with a pressure of 19±2 atm as implied by the recent Soviet probe. Either the pressure is considerably greater than this, or other gases that are more effective microwave absorbers are present.

1. Introduction

Radar observations have been made of the moon, Venus, Mercury and Mars over a wide range of wavelengths (Pettengill and Shapiro, 1965; Evans, 1966; Eshleman, 1967; Pettengill, 1968). Observations of Venus at either very long or very short wavelengths hold special interest in that they are capable of examining effects introduced by the planetary ionosphere or neutral atmosphere, respectively. This paper summarizes studies of the reflection properties of Venus at 3.8 cm wavelength performed at the Lincoln Laboratory (Karp *et al.*, 1964; Evans *et al.*, 1966; Evans, 1968). The section that follows provides a brief history of the development of these studies.

Comparison of the reflectivity of Venus at this short wavelength with the reflectivity at longer wavelengths suggests strong atmospheric absorption of the 3.8-cm signals. This work is reviewed in Section 3 and in Section 4 measurements of the average reflectivity variation over the planetary disk are discussed. These two types of measurement lead to estimates of the one-way zenithal absorption A in the range 2.5 db $<A<$ 5 db. The consequences of this conclusion on existing model atmospheres for Venus are briefly mentioned in Section 5.

2. History

Attempts to observe radar reflections from Venus at 3.6 cm wavelength were first made during the 1961 inferior conjunction of Venus using the Camp Parks terminal of the Project West Ford communications system (Nichols and Karp, 1964). At that time the transmitter power available was only 12 kW, and proper functioning of the entire radar system was not established until well past the point of close approach. No detection of the reflected signal was made. A second attempt was made in 1962 again using the Project West Ford radar system either as a monostatic radar system or bistatically. Prior to these observations the transmitter power was raised to 40 kW and numerous improvements in the operating procedures were made, which lead to greater confidence that the radar was performing satisfactorily. Failure to detect an echo this second time placed an upper limit on the radar cross section of 10% of the projected area of the disk (Table 1).

A third attempt to detect Venus echoes was made in 1964 using the Project West Ford radar system in the bistatic mode. This time the reflected signals were detected after considerable post rectifier integration. From the intensity of the signals, the cross section was estimated to be 1% (Karp *et al.*, 1964). The spectrum of the echoes was found to be wider than could readily be accounted for in terms of Doppler broadening introduced by planetary rotation. However, later work indicates that this broadening seems to have been instrumental in origin. In 1966 and 1967, the Haystack radar system (Weiss, 1965) was employed to study Venus at 3.8 cm wavelength (Table 1). The parameters of the radar systems employed for these three successful series of mea-

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[1] Operated with the support of the U. S. Air Force.

TABLE 1. Summary results of radar cross-section measurements of Venus.

Date of inferior conjunction	Sensitivity of apparatus relative to 1961	Radar cross section (% of projected area of disk)	Observers
1961	1	—	Unpublished
1962	5	<10%	Unpublished
1964	10	~1%	Karp *et al.* (1964)
1966	50	1.2%*	Evans *et al.* (1966)
		1.7%	Evans (1968)
1967	300	1.75%	This paper

* Revised later.

surements are compared in Table 2. The overall improvement in radar performance relative to the first attempt in 1961 is given in Table 1. The later measurements profited considerably from the successive increases in the sensitivity of the apparatus, and thus the reliability of the conclusions reached has improved with time also.

3. Radar cross section of Venus

The echo power P_S in watts available at the input terminals of the radio receiver in a radar system following reflection from a planet is

$$P_S=\frac{P_tGA\sigma}{(4\pi R^2)^2}, \tag{1}$$

where P_t is the peak transmitter power, G the transmitting antenna gain in the direction of the target, A the collecting area of the receiving antenna for signals arriving from the direction of the target, σ the radar cross section of the target, and R the range to the target. The radar cross section σ defined by Eq. (1) may be stated as the projected area of a metal sphere which if placed at the same position as the target would yield the same reflected power at the receiver. For a planet where the radius a is much larger than the radar wavelength λ,

$$\sigma=g\rho\pi a^2, \tag{2}$$

where g is a directivity factor which takes into account the ability of the surface to backscatter favorably and ρ is the Fresnel reflection coefficient for normal incidence. The reflection coefficient is given by

$$\rho=\left|\frac{\sqrt{\epsilon}-1}{\sqrt{\epsilon}+1}\right|^2, \tag{3}$$

where ϵ is the (complex) relative dielectric constant. In the case of the planets studied thus far, the largest part of the echo power is reflected from the smoother undulating portions of the surface occupying the central region of the disk where the rays are nearly normal to the mean surface (Evans, 1966). Under these circumstances the term g becomes

$$g=(1+\alpha^2), \tag{4}$$

where α is the rms surface slope (Hagfors, 1964). Since typically $\alpha\sim 0.1$, g is indistinguishable from unity, and thus measurements of σ may be interpreted in terms of the dielectric constant ϵ for the planetary surface.

Measurements of the cross section of the moon and Venus are shown in Figs. 1 and 2, respectively. In the case of the moon, the values reported at the longest wavelengths may be suspect because of signal fading introduced by the terrestrial ionosphere during the measurements (Hagfors and Evans, 1968). Thus, for the moon σ may be taken as 7% irrespective of wavelength. Interpreting this cross section in terms of reflection from a single interface yields $\epsilon=2.8$. Actually, it is believed that the situation for the moon is more complex and that the properties of the surface layer change with depth. The relative constancy of σ is believed in part to be attributable to an increase in the value of g, arising from the greater roughness of the surface relative to the

TABLE 2. Parameters of Lincoln Laboratory radar systems employed to study Venus at X band.

	June 1964	January 1966	August 1967
Station (s)	Camp Parks/Millstone	Haystack	Haystack
Frequency	8350 MHz	7750 MHz	7840 MHz
Wavelength	~3.6 cm	~3.9 cm	~3.8 cm
Antenna diameter	60 ft	120 ft	120 ft
Antenna gain	59.8 db	66.1 db	66.1 db
Beamwidth	0.14°	0.07°	0.07°
Maximum average transmitter power	40 kW	105 kW	250–400 kW
System temperature on Venus	74K	~120K	65K
Total waveguide and other losses		0.5 db	0.5 db

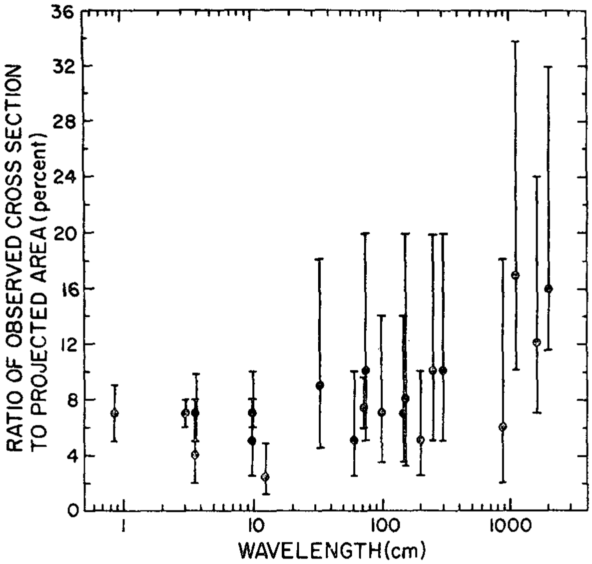

Fig. 1. The radar cross section of the moon, expressed as a percentage of the projected area of the disk as a function of wavelength (Hagfors and Evans, 1968). The measurements at wavelengths ≥10 m are difficult to make because of the effect of the earth's ionosphere and if these values are ignored, the remainder show no systematic wavelength dependence.

wavelength as one goes to shorter wavelengths, which offsets a reduction in the value of ρ arising from the reduced penetration of the signals (Hagfors and Evans, 1968). While the data are less abundant, values of σ obtained for Mercury and Mars are also in the region of 7–8% (Pettengill, 1968).

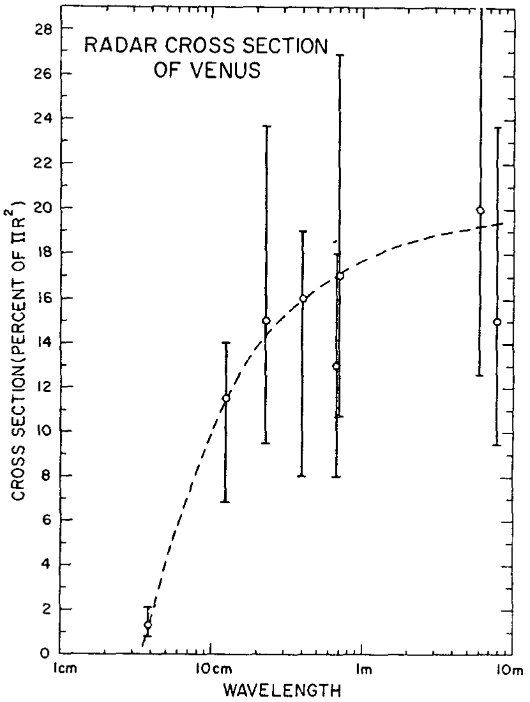

Fig. 2. The radar cross section of Venus vs wavelength (Evans, 1968). At wavelengths ≥23 cm, Venus has a higher reflectivity than the moon (Fig. 1) suggesting a denser or more compact surface layer. The rapid falloff at shorter wavelengths is here attributed to absorption in the planetary atmosphere.

The cross section of Venus observed at long wavelengths (~15%) implies a surface dielectric constant $\epsilon = 4$–5 (Pettengill, 1968). This suggests that unlike the moon and probably Mars, the surface material on Venus is not porous to any considerable depth, or alternatively, it is not completely erroded into fine particles. It seems, therefore, that Venus has a more compact surface than the moon and, consequently, the penetration depth of the signals at all wavelengths will be less. This being so, we would not expect a large variation in the reflection coefficient ρ with wavelength as implied by the results for σ in Fig. 2. Adopting a value $\sigma = 15\%$ for decimeter wavelengths, the results of Fig. 2 could be explained by assuming approximately 1.2 db two-way absorption at 11.5 cm wavelength and 9.5 db two-way absorption at 3.8 cm. When the absolute accuracy of the measurements is considered, the difference in the cross section at these last two wavelengths may be stated as 8±3 db, since at both wavelengths the calibration of the radar system is known only to ±2 db (Carpenter, 1966; R. P. Ingalls, unpublished).

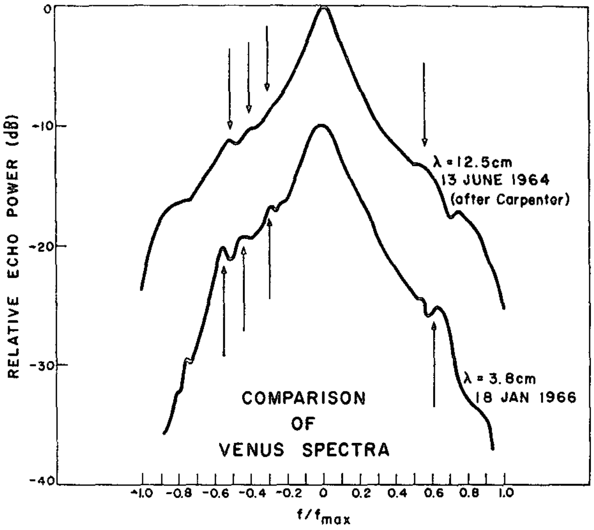

Fig. 3. Echo power spectra observed for Venus at 12.5 cm wavelength (Carpenter, 1966) and 3.8 cm (Evans *et al.*, 1966). These plots show the spread in the echo power arising from the Doppler broadening introduced by the planetary rotation. Arrows indicate locations in the spectra of signals arising from anomalously bright scattering regions on the disk. These features are seen to move with time in a manner consistent with their being attached to the surface and their detection provides one (of several) arguments for believing that the signals are reflected from the surface at both wavelengths (Evans *et al.*, 1966).

4. Radar limb darkening

The radar reflectivity over the planetary disk may be explored in a number of different ways [see, for example, Green (1968)]. In the case of Venus, this distribution

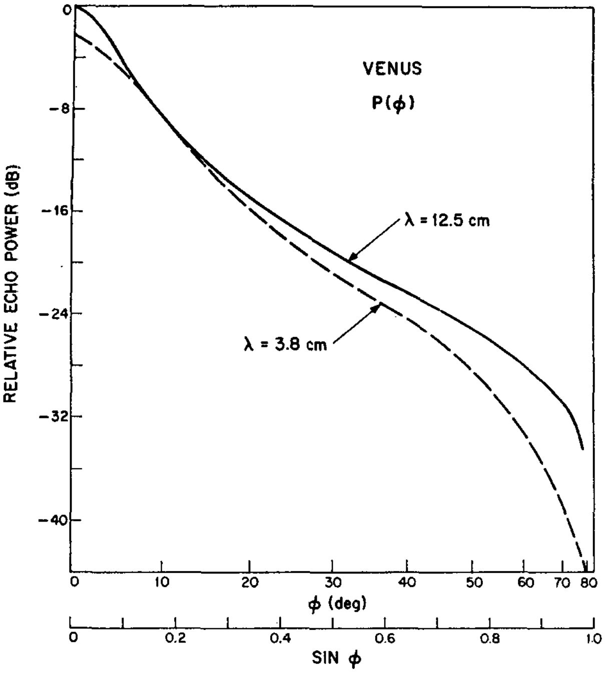

FIG. 4. The mean angular power spectrum for Venus echoes observed at 12.5 cm and 3.8 cm wavelengths. These curves show the relative reflectivity of unit surface area as a function of the angle ϕ between the ray and the surface normal. They have been derived from the mean of a large number of spectra such as those shown in Fig. 3 and adjusted to match near $\phi = 10°$. The lower value for the 3.8-cm curve for $\phi > 20°$ is believed to be indicative of the increasing amount of absorption occurring at this wavelength for the rays that penetrate the atmosphere obliquely.

has been explored at 12.5 and 3.8 cm wavelengths by determining the power frequency spectra of the signals following reflection. Owing to the apparent spin of the planet with respect to a terrestrial observer, a monochromatic signal transmitted from earth is Doppler broadened on reflection. Fig. 3 compares spectra obtained at the two wavelengths. The irregularities in these spectra are believed to be caused by the presence on the disk of anomalously bright reflecting regions.

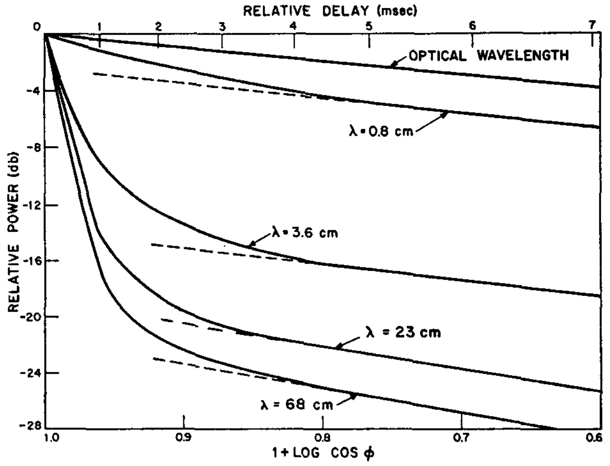

FIG. 5. The angular scattering law observed for the moon at various wavelegths. In the case of the moon, the limbs become progressively brighter with respect to the center of the disk as the wavelength is reduced. From this empirical test as well as from a thenoretical standpoint, the opposite behavior encountered for Venus (Fig. 4) seems difficult to explain unless absorption in the Venus atmosphere is invoked.

We may define a function $\bar{P}(\phi)$ called the angular power spectrum, which is the power reflected per unit surface area into unit solid angle for unit incident flux when viewed at an angle ϕ with respect to the mean surface normal. When defined in this fashion, a surface covered with isotropic scatterers would obey the law

$$\bar{P}(\phi) \propto \cos\phi. \qquad (5)$$

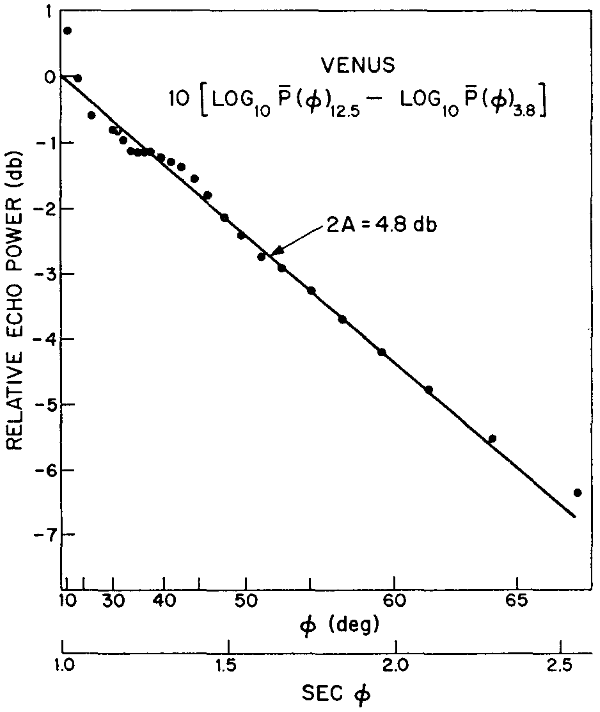

FIG. 6. The difference of the two curves shown in Fig. 4 is here plotted as a function of the secant of the local zenith distance ϕ. The linear dependence for $\phi < 60°$ suggests that the difference in the two-way zenithal absorption is 4.8 db. For $\phi > 60°$, the secant dependence is expected to break down owing to the significant bending of the rays that occur at large zenith distances.

The function $\bar{P}(\phi)$ can be recovered from spectra such as those shown in Fig. 3 by a suitable transformation (e.g., Evans *et al.*, 1966). Fig. 4 shows curves obtained for $\bar{P}(\phi)$ from mean echo power spectra obtained at 3.8 cm wavelength in 1967 (unpublished) and at 12.5 cm in 1964 (Muhleman, 1965). At both wavelengths it is evident that the dependence is much steeper than that given in Eq. (5). The two curves in Fig. 4 have been adjusted to overlap near $\phi = 10°$. The behavior for $\phi < 10°$ is dissimilar, probably because the nature of the terrain occupying the subradar point during the two sets of measurement was somewhat different. It can be seen that for $\phi > 20°$, the 3.8-cm curve falls off more rapidly than the 12.5-cm law.

Fig. 5 shows curves obtained for $\bar{P}(\phi)$ in the case of the moon. The curves have been normalized near $\phi=0°$, and show the opposite type of wavelength dependence to that exhibited in Fig. 4. In the case of the moon the reflectivity of the limbs relative to the center is found to increase with decreasing wavelength. This is attributed to the presence on the surface of fine-scale roughness in which there is an increasing amount of structure having smaller and smaller scales (Hagfors and Evans, 1968). The behavior shown in Fig. 5 is what can be expected for most natural surfaces and thus the opposite behavior exhibited by Venus (Fig. 4) is difficult to explain, unless it is attributed to limb darkening at the shorter wavelength caused by atmospheric absorption. If this is the case, then the difference between the two curves should depend upon the secant of the local zenith angle ϕ. We have tested this hypothesis in Fig. 6 where we show that for $\phi<60°$ there is indeed a secant law dependence. The difference in the two curves is found to be consistent with a two-way zenithal absorption of 4.8 db. (For $\phi>60°$, we expect a departure from a simple secant law because the refraction of the rays in the atmosphere of Venus should become large.)

The estimate of the two-way zenithal absorption obtained here must be a lower limit because 1) there may already be some absorption at 12.5 cm wavelength, and we are only examining the difference, and 2) the intrinsic scattering law of the surface may change with wavelength (as in the case of the moon) to cause the limbs to be *more* reflective at the shorter wavelength (in the absence of an atmosphere).

The experimental accuracy associated with the estimate of the two-way zenithal absorption implied by these results is about ±1 db. Thus, when this result is combined with the cross section results (Section 3), it would appear that the difference in the two-way absorption at 3.8 and 12.5 cm wavelengths lies between 5 and 8 db.

5. Discussion

The atmospheric attenuation of radiowaves at 3 cm wavelength in a CO_2 atmosphere has been discussed among others by Barrett (1961) and by Barrett and Staelin (1964). Since CO_2 is a symmetrical molecule possessing no dipole moment, it is not a resonant absorber, and can be made to absorb only in a transient manner, i.e., during the course of a collision. The absorption coefficient thus varies with the square of the pressure. Calculations performed by Barrett (1961), Kuzmin and Vetukhnovskaya (1968) and others suggest that the microwave emission spectrum of Venus is consistent with a surface pressure of the order of 20–30 atm of CO_2 provided that the surface temperature is raised to 650–700K. This model cannot, however, account for the absorption at 3.8-cm radar signals inferred from the measurements reported above. If the Soviet pressure and temperature curves are extrapolated to higher values, then it would appear that the total absorption implied by the radar results can be attained when the surface pressure is raised to ~100 atm (Kuzmin and Vetukhnovskaya, 1968; Thaddeus[2]). This value depends somewhat upon the assumptions made concerning the presence of water vapor and the precise way in which the temperature and pressure curves are extrapolated. Alternatively, the observed absorption can be achieved by introducing into the atmospheric model a resonant microwave absorber. Water vapor is one such molecule, but limits on the amount that may be invoked exist from 1) the presence of a detectable absorption line in the microwave emission spectrum at 1.34 cm wavelength, and 2) the Soviet probe results which seem to preclude H_2O as the responsible absorber. Other possibilities that have been suggested are aqueous HCL clouds (Hunten[3]) or ammonia clouds (Rea[4]).

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