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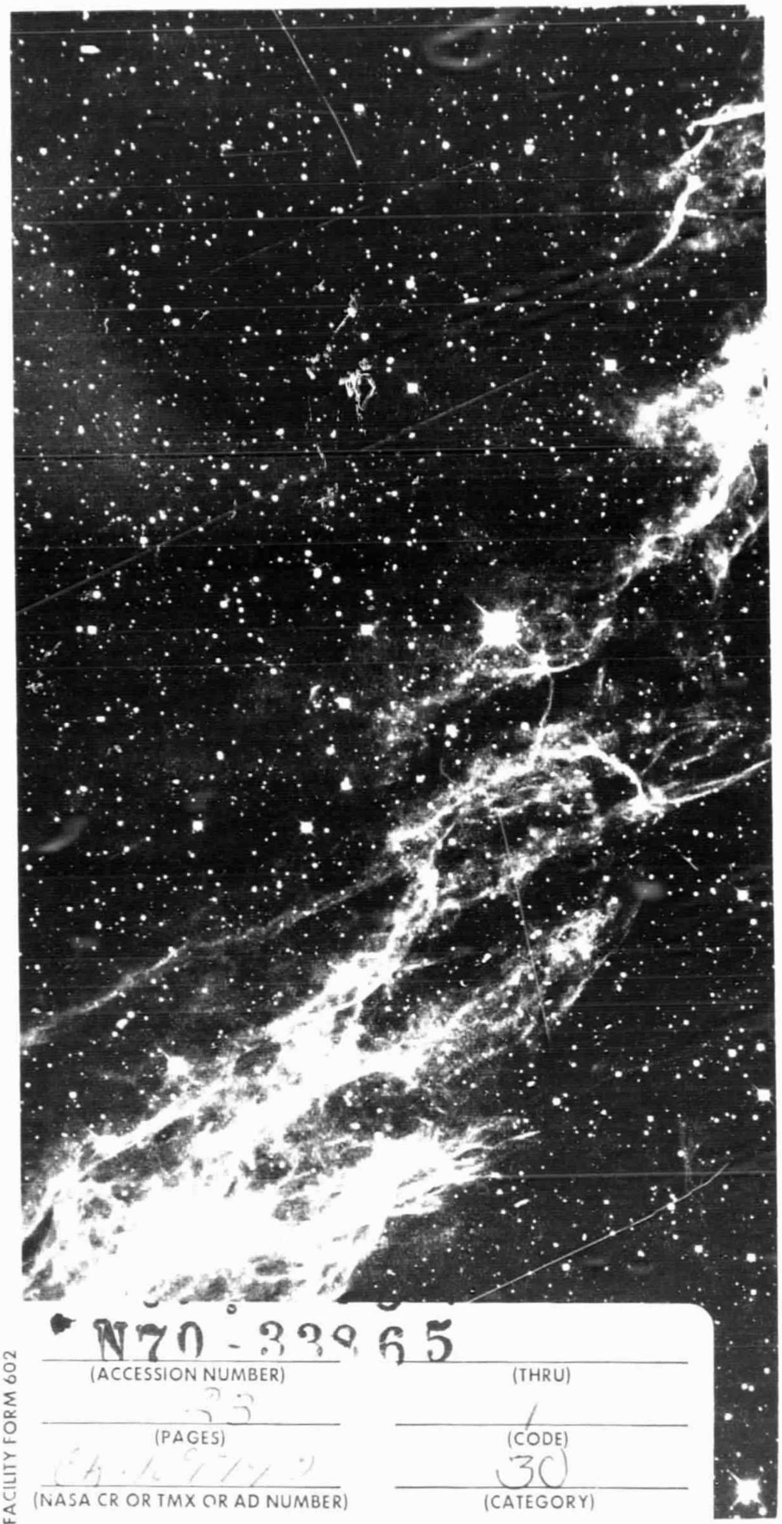

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RADAR EXPLORATION OF VENUS

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RADAR EXPLORATION OF VENUS

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FOREWORD

This technical memorandum results from a short study of spacecraft radar systems suitable for the Planetary Explorer Class of Mapping Orbiters at Venus. The details of the system recommended have been included in the Goddard Space Flight Center submissions to the Space Science Board of the National Academy of Sciences in June 1970. The memorandum reports the underlying background which culminated in the Planetary Explorer recommendations. It treats the broad questions of exploration of the Venus surface using radar.

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1. INTRODUCTION

Remote sensing of the surface of Venus is restricted by the clouds to microwave and longer wavelengths. Both active and passive measurements at long wavelengths have been made from the Earth but with only very gross surface resolution. During the 1970's it is anticipated that Venus will be investigated with orbiting missions and it is important to define the role that radar can play in these missions. This document attempts to place in perspective the different modes of radar operation, to compare their respective contributions and to identify their major system requirements. It results from a request by NASA to define a useful set of radar experiments which would be compatible with the Planetary Explorer spacecraft.

The datum from which spacecraft radar experiments should be considered is that provided by Earth based measurements of Venus. Earth based radar has provided the only available information on the rotation rate of Venus which is approximately 243 days. It is very nearly in synchronous lock with the Earth and presents almost the same face to the Earth at each opposition. Similarly a very accurate measure of its diameter has been obtained from Earth based measurements. The remaining knowledge deduced from radar reflection characteristics imply that Venus is smooth with a few pronounced surface features or rough patches. There are clear differences in the reflectivity of Venus as a function of wavelength going from some 20% at 6m down to about 1% at 3.6cm. The atmosphere may be absorbing the shorter wavelengths and a number of model atmospheres have been proposed to account for this. At long wavelengths the high radar cross section and the dielectric constant (ε = 3.5-5) implies solid rocks, possibly silicates, rather than an extensive regolith or large expanses of liquids. Computations of the average slopes on Venus indicate about 7-8° compared with 10° for the Moon.

The major drawback with Earth based radar measurements is the limited spatial resolution which can be obtained. Current systems using Arecibo or Goldstone, provide about 100 km resolution and are limited to the Earth facing hemisphere and to regions within about ± 30° of the Venusian equator. The best resolution is obtained at the sub-Earth point at conjunction. With currently planned improvements in these systems it is anticipated that a resolution between 1 and 5 km can be obtained from Earth within latitudes of about ± 10° and in the region of the conjunction sub-Earth point. To obtain this type of regional scale resolution over the whole planet will clearly require a spacecraft radar system.

2. RADAR INFORMATION CONTENT

There are five properties of a reflected radar signal which are used to derive information about the reflecting surface. These five properties are shown in Table 1. However, considerable deduction is required to translate the properties of the signal into meaningful parameters of the planet. The time delay is the simplest to interpret and for spacecraft systems can be used, together with a knowledge of the orbit, to map surface elevations. If adequate coverage is available topographic maps and 3 dimensional surface geometry should be determinable.

The doppler shift in the carrier wave is a direct measure of relative radial velocity of the surface with respect to the receiver. From this can be deduced the rotation rate of the planet and the geometrical location of specific points on the reflecting surface but with some possible ambiguity.

The shape of the returned pulse is characterized by the rise time and the decay time of the signal. This may be measured directly in time (nanoseconds) or as a rate of change of doppler shift. In both cases it is related to the roughness of the surface

TABLE 1 RADAR INFORMATION CONTENT

BASIC PROPERTY	MAJOR DEPENDENCY	DESIRED INTERPRETATION
Time Delay	Distance from Transmitter to Receiver	Topographic Map Surface Geometry
Doppler Shift	Velocity of Surface with Respect to the Receiver	Rotation Rate Surface Geometry
Pulse Shape (Rise and Decay)	Roughness of Reflecting Surface Size of Reflecting Area	Specular or Diffuse Resolution Average Slopes
Pulse Intensity	Reflectivity (Dielectric Constant) Geometry	Rock Types Physical State
Depolarization	Roughness of Reflecting Surface	Specular or Diffuse Brenster Angle

compared to the incident signal wavelength and can be used to deduce whether specular or diffuse reflection is taking place. An indication is also given of the size of the area that is reflecting the signal which is interpretable in terms of both the surface resolution being obtained and the average surface slope being observed.

The intensity of the returned signal is a function of the inherent dielectric constant of the reflecting surface and of its topography. If the geometry and surface roughness can be determined from the pulse shape, then it is possible to compute the dielectric constant. This is a crude method of identifying surface materials and their physical state.

Finally by measuring the depolarization of the initially polarized signal, deductions can be made on the nature of the reflection, specular or diffuse, and on the roughness of the surface.

The above five properties are common to all pulsed radar systems, whether Earth based, bistatic or monostatic on a spacecraft. The ease or difficulty of interpretation from these properties is strongly related to the signal to noise ratio of the system. The figures given above for Earth based resolution in fact relate to the limiting useable signal to noise ratio, including integration of the signal. Throughout this paper, it is assumed that a S/N ratio of 6 is obtained with integration, while integrating the signal can provide, approximately an improvement of a factor of 10. The principal advantage of spacecraft radar systems is that their proximity to the target affords the opportunity for high spatial resolution and an accurate knowledge of the location of the part of the surface reflecting the signal at any instant.

3. VENUS RADAR MEASUREMENTS

Radar and microwave measurements are the only synoptic measurements available for determining the surface conditions on Venus. They must necessarily be supplemented by in situ analysis from landers but radar should both precede and follow such direct surface measurements. Ultimately the desire is to obtain maps of the surface of Venus indicating topography, rock units, roughness, average slopes and the physical and chemical state of the constituents. A progression with time will require increasing spatial resolution at the possible expense of planetary coverage. Table 2 shows four categories of measurements defined by the desired range of surface resolution. The vertical resolution is related directly to the desired horizontal scale and it does not necessarily represent the capability of a radar system. The special emphases are related to the capabilities of Earth based radar and also imply a selectivity of coverage which will arise as more understanding of the Venusian surface is obtained. The theory and interpretation appears to be adequately understood provided the resolution is large compared to the wavelength of the signal. However, for the very high resolution requirements of local and detailed measurements it is not clear that sufficient knowledge is presently available to provide adequate interpretation of the returned signal.

4. PLANETARY REFLECTION CHARACTERISTICS

The characteristic of a reflecting surface which has the most profound impact on the measurement system is whether it is specular or diffuse. Specular reflection can be likened to reflection from a dirty mirror whereas diffuse reflection is like that from a sheet of white paper. In actual practice no planet can be expected to be uniform in its reflection characteristics if for no other reason than because of surface structure, nor will

TABLE 2 RADAR MEASUREMENT REQUIREMENTS

(Topography, Material Identification, Physical State, Roughness, Slopes)

	GROSS	REGIONAL	LOCAL	DETAILED
Horizontal Resolution	100-500 Km	1-20 Km	100 m	1 m
Vertical Resolution	1-5 Km	10-50 m	1-5 Km	1-5 cm
Special Emphasis: *				
Coverage	Total	Total	10%	1%
Latitude	≥ 30°	≥ 10°	All	All
Longitude	Farside	Farside	All	All
Theory and Interpretation	OK	OK	?	?

* To overcome limitations of Earth-based systems

it be perfectly specular or diffuse. Furthermore its reflection characteristics will be a function of wavelength. Typically the Moon is an almost ideal diffuse reflector at visible wavelengths while at 6 meter wavelengths it appears to be a specular reflector. At the wavelengths being considered for spacecraft radar (13 cm) it is not clear whether Venus will be predominantly specular or predominantly diffuse. It is, therefore, important to consider the relevant relationships for both cases. Table 3 summarizes the principal effects for each case.

Specular reflection follows the classical reflection laws and can be simulated by ray traces. The signal received in an antenna can come from only a specific point on the planet defined by the angles of incidence and reflection. For bistatic systems this point is on the surface and in line with the Earth (transmitter) and the spacecraft. For monostatic systems this point is vertically beneath the spacecraft (vertical incidence) and thus side looking radar will not function for specular reflection. The reflected signal is the result of phase coherent integration at the receiving antenna from points within the first fresnel zone. Within this zone contributors are in phase although some contribution can come from outside the zone if there is not complete phase cancelling by these outside contributors. The reflected signal strength is defined by the beam leaving the fresnel zone and is independent of the antenna size provided the beam width is large enough. This must be modified slightly for a spinning spacecraft since the beam width must now be wide enough to accept signals from the specular point despite the rotation. The area of the fresnel zone is $\sqrt{2\lambda R}$ where λ is the wavelength and R is the distance between the reflecting area of the surface and the spacecraft, and which for $\lambda = 13$ cm and $h = 1000$ km gives a resolution of about 1/2 km. In practice, using a bistatic system for the Moon, only a much larger resolution of about 100 km could be obtained for predominantly specular reflection. A rule of thumb has been to assume that facets over a large area contribute to the signal

TABLE 3 BASIC PROPERTIES OF RADAR REFLECTION

SPECULAR	DIFFUSE
Only at Specific Angles of Incidence and Reflection	Any Look Angle Including Side Looking
Signal Strength Independent of Field of View (Antenna Beam Width)	Signal Strength Depends on Area Viewed.
Resolution Defined by Reflecting Surface	Resolution Defined by Signal Processing (Doppler or Time).
Characteristic Polarization	Random Polarization.

and that a relation αR seems to hold where α is the average surface slope equalling 8-10% for Venus, and R is the distance to the surface for low altitudes. When the altitude is greater than the planet radius then a limiting value of $R = R_V$ is assumed. This can be converted to αh for monostatic vertical incidence systems. For diffuse reflection the resolution is determined by the signal processing and doppler analysis. However, it is limited by the pulse width to $2\sqrt{c\tau h}$ where c is the velocity of light and τ is the pulse width when vertical incidence is employed. To gain higher resolution from a fixed altitude for diffuse reflection it is necessary to reduce the pulse width and consequently worsen the signal to noise ratio. A typical pulse width of 130μsecs. gives 400 km resolution and 300 nanoseconds gives about 20 km resolution from a range of 1000 km. Diffuse reflection will cause appreciable distortion of the transmitted pulse. The leading edge will rise slowly reaching a plateau in about one pulse width and its decay time will be stretched out by backscattering from the outermost areas in the beam.

In interpreting the reflected signal, one of the important deductions is of the dielectric constant of the reflecting surface. For specular reflection ϵ is given by $\epsilon_o \tan^2 \theta_B$, where ϵ_o is the dielectric constant of free space and θ_B is the brewster angle given by polarization measurements. For diffuse reflection ϵ is given by $\epsilon_o \left(\frac{1 - \rho}{1 + \rho}\right)^2$ where ρ is the voltage reflection coefficient.

Above all else however, the differences between specular and diffuse reflection show up in the basic radar equations used for computing the strength of the reflected signal. The part of the equation which varies most is the assumed radar cross section. The overall equation for signal strength can be written as:

$$P_r = P_I \times L_R \times A_r$$

where P_r = total signal power received in the antenna

P_I = Incident power density on the surface = $\dfrac{P_t\ G_t}{4\pi\ r^2}$

L_R = loss due to reflection and travel to the antenna from the surface

A_r = effective area of the antenna = $\frac{G_r \lambda^2}{4\pi}$

where P_t = transmitted power (carrier wave or peak pulse)

G_t = transmitter antenna gain

G_r = receiver antenna gain

r = distance from transmitter to surface

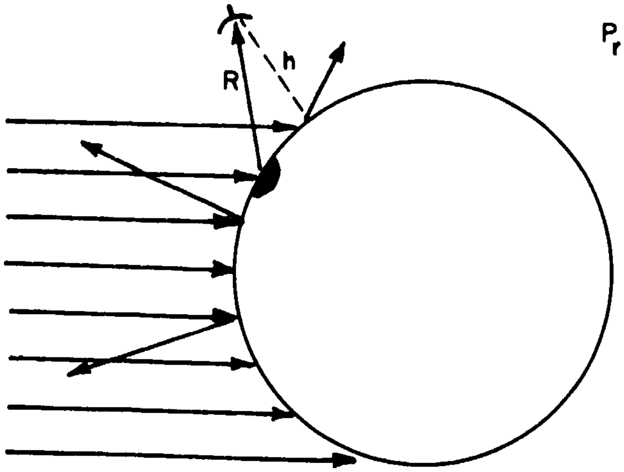
For both specular and diffuse reflection the resulting equations are shown in Figures 1 and 2. It should be noted that side looking radar is only applicable with diffuse reflection and then the slant range R should be used instead of h in the equations.

5. COMPARISON OF RADAR MODES

Bistatic radar operates best when the signal is transmitted from Earth and received on the spacecraft. The Aercibo or Goldstone antennas operating at full power have been assumed for transmitting the signal and an omnidirectional antenna on the spacecraft for receiving the reflection. If the reflection is predominantly specular then the signal will be received from the specular point on the planet with respect to the Earth and the spacecraft and a spot size of about 200 km diameter may be anticipated (L. Tyler, Private Communication). Doppler filters will be required to locate the specular point. Also if the reflection is diffuse then it will be difficult, without doppler filters, to resolve anything within view of the spacecraft i.e. about one quarter of the planetary surface.

Monostatic radar on the spacecraft offers the most in terms of resolution, coverage and range of useable altitudes. It may be vertical incidence or side looking (diffuse only) and high resolution can be obtained by the addition of doppler filters.

BISTATIC

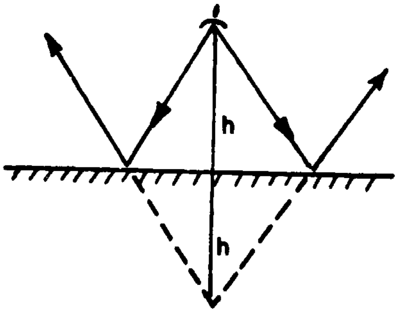


$$P_r = \frac{P_t \; G_t}{4\pi R^2_{E-V}} \cdot \frac{\sigma_B |\rho|^2}{4\pi (R_v + h)^2} \cdot \frac{\lambda^2}{4\pi}$$

ASSUMPTIONS:

APPARENT SOURCE IS WHOLE AREA OF PLANET
$\sigma_B = \pi R_v^2$ ACTING AT CENTER OF PLANET
RESOLUTION $\sim \alpha R$
REFLECTION COEFF $\sim$ ·14
OMNI ANTENNA, $G_r = 0$ db
DOPPLER FILTERS TO LOCATE SPECULAR POINT

MONOSTATIC
($h \ll R_v$)

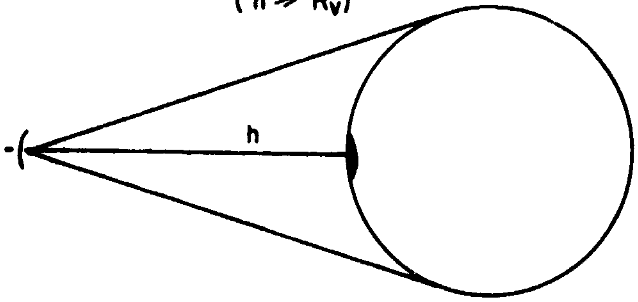


$$P_r = \frac{P_t \; G_t}{4\pi (2h)^2} \cdot |\rho|^2 \cdot \frac{G_r \lambda^2}{4\pi}$$

ASSUMPTIONS:

FLAT MIRROR REFLECTING SURFACE,
APPARENT SOURCE 2h FROM RECEIVER.
RESOLUTION $\sim \alpha h$
$G_r = G_t$

MONOSTATIC
($h \gg R_v$)



$$P_r = \frac{P_t \; G_t}{4\pi (R_v/2 + h)^2} \cdot \frac{\pi R_v^2 \, |\rho|^2}{4\pi h^2} \cdot \frac{G_r \, \lambda^2}{4\pi}$$

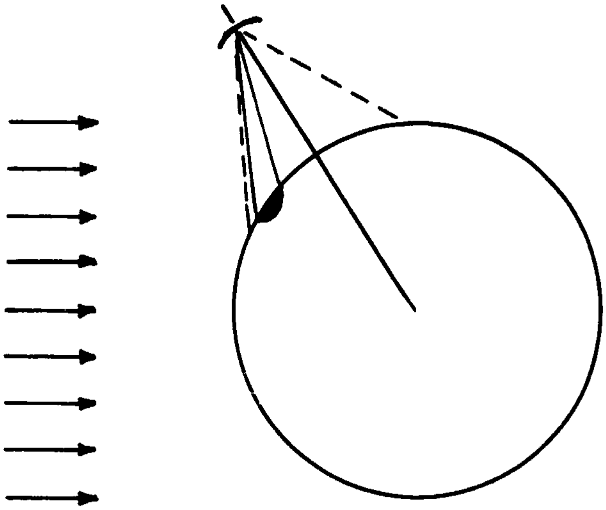
ASSUMPTIONS:

APPARENT SOURCE IS WHOLE AREA OF
PLANET πR_v^2 AT $R_v/2$ BENEATH SURFACE
RESOLUTION $\sim \alpha h$
$G_r = G_t$

FIGURE 1. BASIC RADAR EQUATIONS; SPECULAR REFLECTION

BISTATIC

$$P_r = \frac{P_t G_t}{4\pi R_{E-V}^2} \cdot \frac{\sigma |\rho|^2}{4\pi h^2} \cdot \frac{\lambda^2}{4\pi}$$

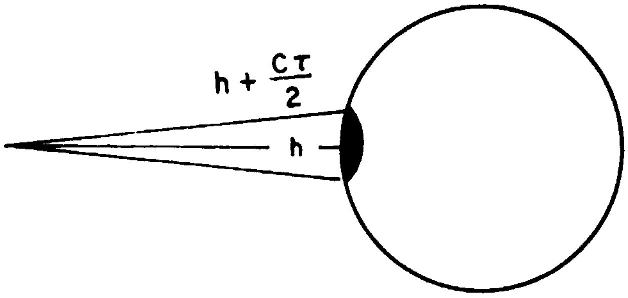


ASSUMPTIONS :

DOPPLER FILTERS TO LOCATE AREAS ~ 200 KM^2
CROSS SECT. $\sigma = \pi/4 \ (200)^2$ KM^2
REFLECTION COEF $|\rho|^2 \sim .10$

MONOSTATIC

$$P_r = \frac{P_t G_t}{4\pi h^2} \cdot \frac{|\rho|^2 (\pi C\tau h)}{4\pi h^2} \cdot \frac{G_r \lambda^2}{4\pi}$$



ASSUMPTIONS :

PULSE WIDTH LIMITED RES^N = $2\sqrt{C\tau h}$
NO DOPPLER FILTERS
TIME GATES FOR ANALYSIS

FIGURE 2. BASIC RADAR EQUATIONS; DIFFUSE REFLECTION

For diffuse reflection the side looking mode, using time discrimination in a radial direction, may be feasible and it may be unfocused (resolving in one horizontal direction only) or focused (imaging radar). Table 4 summarizes the signal to noise and resolution characteristics of these systems and forms the preliminary basis for selection of spacecraft radar systems.

In terms of the current needs for knowledge of Venus it is strongly recommended that the state of the art of Earth based systems be pushed as far as possible. However for adequate coverage, spacecraft radar systems will be required. Both gross measurements and regional measurements are considered in more detail in the next two sections.

6. GROSS RADAR MEASUREMENTS

The more detailed specifications for bistatic and monostatic systems for gross measurements (100-500 km resolution) are shown in Table 5. Either system would be adequate if the reflection is predominantly specular. However, if it turns out to be diffuse at the wavelengths being considered (13 cm) then the bistatic system will give no information at all on a scale of 200 km. On the other hand, the vertical incidence monostatic system still has a good signal to noise ratio at 1000 km altitude and can suffer the R^3 loss out to about 5000 Km. The lightest system is the bistatic for which the total weight of 50 lbs. is made up principally of two redundant recorders, a receiver and a low weight antenna. However, the bistatic system is the hardest to interpret because of the complex geometry of the specular point with respect to the spacecraft. Furthermore its coverage is limited to about 70% of the planet even if adequate signal to noise ratio is available throughout the full 240 day synodic period of Venus.

TABLE 4 COMPARISON OF RADAR MODES

MODE	REFLECTION	SIGNAL TO NOISE RATIO (db) 3db = x 2.			
		GROSS 200-500Km	REGIONAL 1-20 Km	LOCAL 100 M	DETAILED 1 M
Earth Based	Specular	+4 db	Limited	-	-
	Diffuse	0 db	Limited	-	-
Bistatic	Specular	-1 db	-	-	-
(Omni antenna 1000 Km alt)	Diffuse	-20 db	-	-	-
Vertical Incidence	Specular	+14 db*	-7 db**	-	-
(Omni antenna 1000 Km alt)	Diffuse	0 db	-36 db	-	-
Side Looking Unfocused	Specular	-	-	-	-
	Diffuse	-	-40 db	Small***	Small***
Side Looking Focused	Specular	-	-	-	-
	Diffuse	-	-	V.Small***	V.Small***

* By adding 10 db antenna, useable to 20,000 Km ($G_t\ G_r = 20$ db)

** By adding 28 db antenna, useable to 50,000 Km ($G_t\ G_r = 56$ db)

*** High power or high gain antenna required

\- = NOT APPLICABLE

TABLE 5 RADAR FOR GROSS MEASUREMENTS (200-500 Km)

CHARACTERISTIC	BISTATIC		VERTICAL INCIDENCE	
	SPECULAR	DIFFUSE	SPECULAR	DIFFUSE
Basic System	CW + Filters	CW + Filters	Pulse $\tau=130\mu s$	Pulse $\tau=130\mu s$
Antenna Gain(db)	0-Omni*	0-Omni*	10 db HORN	10 db HORN
Antenna Beam Width	360°	360°	~ 50°	~ 50°
Power (Watts)	4×10^5*	4×10^5*	1 Kw Peak 10 W Ave	1 Kw Peak 10 W Ave
Signal (dbw)	-160	-180	-126	-139
Noise (7.6 KHz, $T=10^3 {}^\circ K$)	-160	-160	-160	-160
S/N (1000 Km Alt)	0	-20 db	+34 db	+21 db
Maximum Altitude (Km)	< 5000	~ 700	> 20,000	~ 5000
Resolution (Km)	~ 200	~ 200	~ 200	~ 500
Coverage	~70% in 240 d	~50% in 240 d	100% in 120 d	100% in 240 d
Meas. Arc (400 x 20,000 Km)	~ 180°	~ 60°	360°	107°
Approx. Weight, lbs.	50	50	70	70
Approx. Power, Watts	25	25	50	50

* Transmission from Goldstone $G_t = 60.5$ db,

The vertical incidence system would cost an additional 25 lbs. in a transmitter and three small wide angle horn antennas and would require about 25 watts of additional power. It would not need the 20 or so doppler filters used by the bistatic but otherwise would be the same. The addition of the known geometry from a vertical incidence system offers a simpler interpretation problem and it would provide useful data for either specular or diffuse reflection. In the particular case of specular reflection it offers an excellent gross radar experiment, with full coverage in 120 days, to complement the ground based radar systems.

When the bistatic and monostatic systems were considered for use with the Planetary Explorer program the vertical incidence system seemed the more appropriate. However, further consideration showed that it could be additionally modified to make regional measurements down to 1 km resolution and it was finally selected in that mode. The following section discusses the system in more detail.

7. REGIONAL RADAR MEASUREMENTS (1-20 KM)

Table 6 gives some detailed characteristics of the vertical incidence radar system selected for inclusion as part of the Planetary Explorer Mapping Orbiter payload. It uses a 5 foot diameter antenna which has to be maintained within ± 3° of the vertical for the whole time that measurements are being made. It is a pulse width limited system using a 300 nanosecond pulse width. Otherwise the system is very similar to that used for gross measurements. If the reflection is predominantly specular, the system can be used the whole way around a 400 x 50,000 km orbit. For the diffuse case measurements can only be made over some 90 degrees of the orbit and coverage is restricted. Since it is not known how Venus will reflect at 13 cm this latter case has been assumed for the Planetary explorer experiment.

TABLE 6 RADAR FOR REGIONAL MEASUREMENTS (1-20 Km)

(RECOMMENDED FOR PLANETARY EXPLORER)

CHARACTERISTIC	VERTICAL INCIDENCE	
	SPECULAR	DIFFUSE
Basic System	Pulse τ = 300 ns	Pulse τ = 300 ns
Antenna Gain db	28.5 (5' dia steerable)	28.5 (5' dia steerable)
Power Watts	10 Kw Peak	10 Kw Peak
Signal dbw	-112 @ 1500 Km -130 @ 50,000 Km	-141 @ 1500 Km -168 @ 50,000 Km
Noise dbw	-133	-133
S/N	+21 @ 1500 Km +3 @ 50,000 Km	-8 @ 1500 Km -35 @ 50,000 Km
Maximum Altitude Km	50,000	1,500 Km
Resolution	5 Km	20 Km
Coverage	100% in 120 days	40% in 240 days
Approx Weight lbs.	92	92
Approx Power Watts	60	60

Given this experiment, it is tempting to add a simple omnidirectional antenna and to have the system serve double duty as a gross bistatic system and a regional vertical incidence system. At no more cost it would be possible instead to include low gain antennas which did not need steering and have a gross and regional scale, full coverage vertical incidence system.

8. CONCLUSIONS

Although this has been only a brief study, and has necessarily avoided the many intricacies of radar data interpretation, it has demonstrated the feasibility of radar measurements of Venus down to a resolution of about 1 km. Below this, at a point where the wavelength approaches the desired resolution it is not clear that the present analysis and interpretation techniques will be adequate DOD experience should prove helpful.

Earth based radar has played a major role in the limited exploration of Venus to date and it is strongly recommended that it continue to be improved and utilized.

Bistatic radar, illuminating from the Earth and receiving the reflection on an orbiting spacecraft offers advantages in resolution and coverage over Earth based systems. For an investment of about 50 lbs. experiment weight, about 70% coverage can be achieved at 200 km resolution or better over a period of some 240 days. This performance however assumes a predominantly specular reflection from Venus and if, in actuality, the reflection is diffuse at a 13 cm wavelength then no useful data will be received.

A preferred system is a vertical incidence radar (altimeter) which for about 25 lbs. additional weight (75 lbs total) can perform for either specular or diffuse reflection. And in the specular case will give 100% coverage in 120 days. By adding further antenna gain to this system, regional measurements can be made for either specular or diffuse reflection.

Two major problem areas still exist in defining the radar exploration of Venus. First, it is not known how the planet reflects at 13.5 cm. It would be most appropriate if a simple experiment could be performed on the 1973 Venus/Mercury mission to resolve this. Second, there is no experience in analysing very high resolution planetary radar data. Side looking, coherent systems will certainly be required for this phase but much more experience will be required before a system can be designed for Venus.