Design for a Venus Orbital Imaging Radar Mission

J. R. Rose* and L. D. Friedman†
Jet Propulsion Laboratory, Pasadena, Calif.

A planetary exploration mission to map the surface of Venus is discussed. A review of the Venus exploration program provides a basis for determining the probable scientific requirements for resolution, planetary coverage, etc., for such a mission. From these requirements, the range of possible mission, radar, and spacecraft functional requirements is determined and a single "point" design is investigated in some detail. This point design, which provides full planet mapping at resolutions better than 200 ms, is based on Mariner-class spacecraft technology, including a conventional bipropellant propulsion system, currently under development, capable of delivering the required payload into a 500-km circular Venus orbit. The technology is fundamentally state-of-the-art, using current systems capabilities satisfying the mission requirements.

Nomenclature

BW = bandwidth
ES = Earth-storable
SS = space-storable
SW = swath width
SNR = signal-to-noise ratio
PRF = pulse repetition frequency
RTG = radioisotope thermoelectric generator
b = radar frequency parameter
B_0 = radar acquisition data rate
c = speed of light
C_3 = Earth departure injection energy
C_p = compression ratio = bT^2
D = duty cycle = $T/(PRF)$
f_0 = radar transmitter frequency
Δf = maximum Doppler frequency shift
H = altitude
K_1, K_2 = radar operational constants
velocity change for Venus Orbit Insertion (VOI)
L_a = antenna azimuth dimension
L_r = antenna range dimension
N = number of orbits in mapping cycle
P_a = radar transmitter average output power
P_n = radar noise power
T = radar pulse length
u_a = resolution in azimuth
u_r = resolution in range
v = spacecraft orbital velocity
V_{hp} = Venus approach velocity
ΔV = Velocity change for Venus Orbit Insertion (VOI)
α = atmospheric attenuation
β_a = antenna beamwidth in azimuth
β_r = antenna beamwidth in range
γ = radar wavelength
σ = radar backscattering cross-section
θ = radar side look angle
Δ = fraction of mapping overlap at the equator

Presented as Paper 74-222 at the AIAA 12th Aerospace Sciences Meeting, Washington, D.C., January 30-February 1, 1974; submitted February 27, 1974; revision received October 7, 1974. This paper presents the results of one phase of research carried out at the Jet Propulsion Laboratory, California Institute of Technology, under Contract NAS 7-100, sponsored by NASA. This work represents the application of a technical team's talents over an 8-month period in 1972-1973. The analysis and support of C. Elachi and A. Laderman from the radar design group and of study members representing each of the technical divisions at JPL are gratefully acknowledged.

Index categories: Lunar and Interplanetary Spacecraft Systems, Unmanned; Spacecraft Mission Studies and Economics.

*Member of the Technical Staff.
†Member of the Technical Staff. Member AIAA.

I. Introduction

A. Purpose

THE requirements for and feasibility of a Venus-orbiting spacecraft mission in which the primary scientific sensor is an imaging radar system are to be discussed. The results of previous studies established a) the feasibility of a space-borne microwave imaging radar obtaining surface images, through the Venus cloud cover, of resolution down to the order of tens of meters,[1] and b) the importance and value of the scientific knowledge to be gained by acquiring such data over the entire planet surface.[2]

B. Review of Science Objectives

To establish the mission design requirements, we will summarize here the science rationale for imaging radar.[2] The science cornerstones upon which the VOIR mission was constructed are:

1) Knowledge of planetary surface topography is necessary in understanding the physics of the origin and evolution of Venus and the processes at work on Venus, which aids in understanding similar processes on other terrestrial planets.

2) Surface-feature mapping resolution of different levels provides knowledge of different surface processes.

3) The extensive Earth-based radar surface mapping of Venus will map 20 to 50% of the Venus surface at resolutions of 2 km or better by 1980. Refining the scale to the 100-200 m level admits the study of regional dynamic processes (volcanoes, crater statistics, surface erosion). This information in turn will provide directions as to the next step in the investigative process—targeted landers, atmospheric probes, etc.

C. Mission Design Strategy

This study, examines a point design mission. By identifying important trade-off areas and assessing the options, the study provides an assessment of technology difficulties and design uncertainties for such a mission. The approach produces a nominal mission profile without attempting to optimize the mission parameters.

II. Mission Requirements and Constraints

The VOIR mission designed according to the rationale previously outlined must be evaluated against a set of criteria including the scientific measurement requirements, mission and trajectory constraints, technological capabilities in ground, spacecraft, and radar systems, and reasonable resource availability. For this analysis, two sets of requirements were employed: a design base, which was determined a priori; and derived constraints, which evolved during the course of the investigation.

A. Design Base

Design constraints are as follows: 1) fulfill science requirements for resolution and coverage; 2) no new mission-independent data acquisition capabilities will be required at the 64-m stations of the NASA/Jet Propulsion Laboratory Deep Space Network (DSN); 3) the radar design criteria are established by the Planetary Imaging Radar Study;[1] 4) the spacecraft design for the specified mission will be established with no prior constraints on the use of existing designs or hardware.

B. Derived Constraints and Assumptions

1) The orbital mission lifetime will be 120 days (one half of a Venusian sidereal day). This requires that the spacecraft, on each mapping orbit, map around the entire planet, and that overlapping mapping swaths be taken.

2) The Venus orbit into which the spacecraft is inserted will be a polar, circular orbit with altitude <2000 km. This simplifies the radar design by minimizing the range of the Doppler shift component of the radar echo and by "fixing" the delay time between transmission and reception of the radar signal. This choice also permits simplified antenna, and spacecraft control and pointing requirements.

3) The spacecraft will be three-axis stabilized, referenced to the sun and Canopus, with a gimbaled, articulated antenna for radar mapping.

III. Radar Characteristics

A. Physical Description

A brief summary here of the salient radar operating characteristics[1] will help in the description of the VOIR mission and of the spacecraft system, to be given later. (See Ref. 1 for a detailed discussion of the principles of radar imaging.)

B. Operating Characteristics

The radar geometric parameters, shown in Fig. 1, and the signal parameters define the capabilities of the coherent radar operation. The two principles defining the limits of the system are: 1) signal differentiation, or stability of the system, which limits resolution capability, and 2) the requirement to avoid ambiguous signal return in both range and azimuth which defines the capability of the particular design to meet those limits. The important physical requirements to be determined from these relationships are radar antenna system weight, and volume. A circular cross-section antenna is assumed. The correct choice of frequency is more strongly governed by the transmission and scattering properties of the Venus environment and in turn affects the transmission power requirements. Data requirements are primarily determined by the coverage desired, as will be shown in the next section.

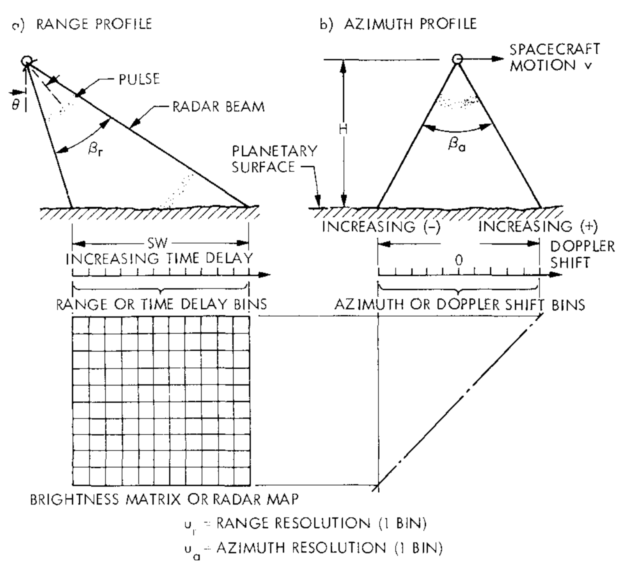

Fig. 1 VOIR radar geometries.

C. Functional Dependencies

Radar frequency

The atmospheric attenuation drives power and size requirements up rapidly at radar frequencies above 3 GHz ($\lambda < 0.1$m). However, radar antenna size increases with λ (Fig. 2), such that long wavelengths are undesirable. The VOIR design wavelength is chosen to be $\lambda = 0.25$m($f_0 \simeq 1.2$ GHz)

PRF constraint

The fundamental constraints on radar system parameters can be expressed as constraints on the PRF.[1] In range it is necessary to limit the PRF to avoid confusing the echo from one pulse returning from the farthest scatterer in the swath (Fig. 1, left-hand side) with that of the next pulse returning from the nearest scatterer. That is, for a given swath width,

$$SW \cong \frac{2H\lambda}{L_r \cos^2\theta} \text{ (narrow beam approximation)} \quad (1)$$

$$\text{PRF} \leq \frac{c \cos^2\theta L_r (l-D)}{4H\lambda \sin\theta} \quad (2)$$

In azimuth, the *PRF* must be large enough to permit at least two samplings per cycle at the largest Doppler shift to be encountered. This is defined by the difference in frequency received from the trailing to the leading edge of the beam,

$$\Delta f \cong (v\beta_a/\lambda) = \text{(narrow-beam approximation)} \quad (3)$$

$$PRF \ll 2v\beta_a/\lambda \quad (4)$$

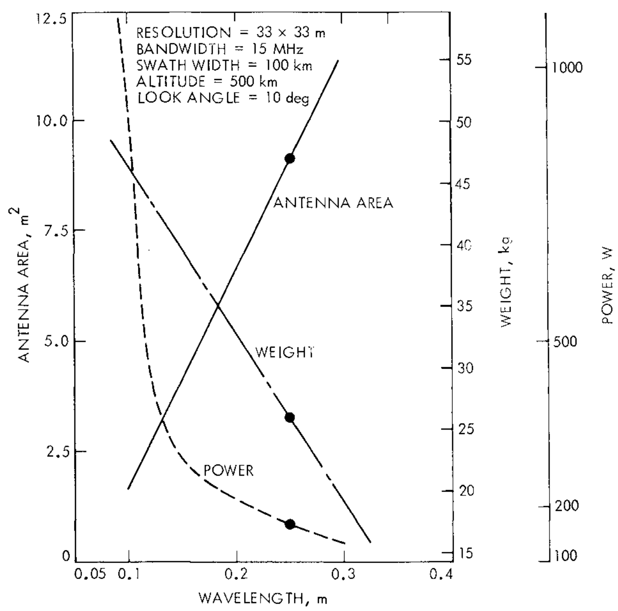

Fig. 2 Antenna area, total radar system dc input power, and weight vs wavelength.

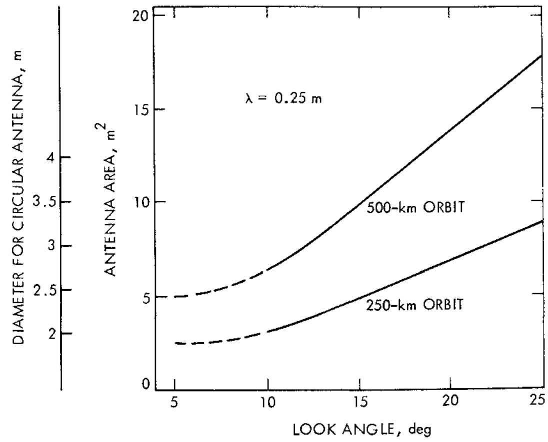

Fig. 3 Minimum antenna area vs look angle and orbit altitude.

Antenna area constraint

In turn, expressing the beamwidth in terms of antenna dimension, the *PRF* constraint leads to the requirement on minimum antenna dimensions,

$$L_r L_a \geq \frac{K_I H V \lambda}{c(1-D)} \; \frac{\sin\theta}{\cos^2\theta} \quad (K_r \approx 11) \tag{5}$$

Figure 3 shows the minimum antenna areas vs look angle.

Resolutions

In both dimensions, resolution is limited by the discrimination of the system. In azimuth, the resolution bandwidth can be considered to be

$$BW_a \simeq \Delta f = v\beta_a / \lambda \tag{6}$$

and hence,

$$u_a = nv / BW_a \simeq K_2 n L_a \tag{7}$$

when n successive samples are presummed, and $K_2 < 0.5$ indicates the effective portion of the antenna beamwidth used. In range, at angle θ, the resolution element on the surface is related to the time discrimination bandwidth by

$$u_r = c / [2(BW_r)\sin\theta] \cong cD / [2(PRF)C_p \sin\theta] \tag{8}$$

D. Radar System Design

The radar system for VOIR is designed under the following assumptions (in addition to the scientific requirements described earlier). 1) A circular cross-section antenna is attractive since existing antenna designs may be applicable; 2) Near-equal resolutions in azimuth and range provide attractive science return; 3) System mass and average power should not exceed 45 kg and 200 w respectively, in order to achieve reasonable spacecraft design characteristics; 4) Orbital altitude should be the minimum acceptable with navigation and atmospheric drag uncertainties, in order to maximize science return for power and mass available; 5) Look angles should be in the range of 10° to 30°, to minimize antenna size and still allow low-power radar transmitter design; 6) Solid state transmitter technology is preferred, to maintain high reliability and long lifetime.

Power requirements

The decrease in power requirements as look angle increases is shown in Fig. 4 for two representative resolutions. The radar system must be sized to the highest resolution requirements. The advantages gained in decreased power are offset by increased antenna size, as shown in Fig. 3, such that

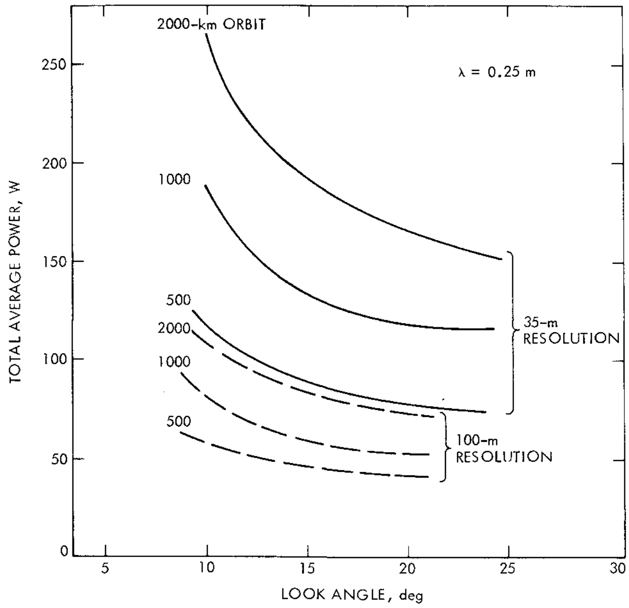

Fig. 4 Radar system power for circular antennas, minimum size.

the choice of look angle must involve a spacecraft system design compromise.

Weight and size

Radar system weight and size are governed by two elements: The radar antenna and the electronics (transmitter/receiver and data system). The transmitter size is highly dependent upon power requirements, and whether a solid state transmitter or traveling wave tube design is required. The VOIR radar system design mass and size will be described in the spacecraft system design section.

Multiple look

Because of the coherent nature of the imaging technique, the image will have a speckled appearance. Therefore, to obtain a good-quality, smooth image, independent "looks" might be needed, leading to an increase in the bit rate required. These looks are obtained by adequate choice of the signal characteristics and proceesing of the echo, and do not require multiple passes over the same area.

IV. Mission Design

A. Opportunity Analysis

The Venus mission opportunities repeat on 8-year cycles (very nearly), and a look at the five opportunities between 1978 and 1985 will represent previous or succeeding 8-year cycles as well. From science program considerations, the early 1980s opportunities have been shown to be especially appropriate.[2] The five opportunities discussed here were chosen by minimizing the combination of required Earth departure injection energy, C_3, and approach velocity at Venus, V_{hp}, providing maximum payload over a 20-day launch window for each opportunity. Figure 5 indicates that the 1979 opportunity will probably yield the minimum available orbital payload due to the high C_3 requirements, and the 1983 opportunity the maximum payload, due to the low C_3 and V_{hp} combination.

B. Launch Vehicle Capabilities

Candidate launch vehicles for this era include the Titan III E/Centaur and the Shuttle/Centaur.‡. Also considered were

‡The interim tug, which will be available for planetary missions in the 1980-1985 time period, is not yet defined. The use of Shuttle/Centaur here represents planned capabilities of the Shuttle/interim tug.

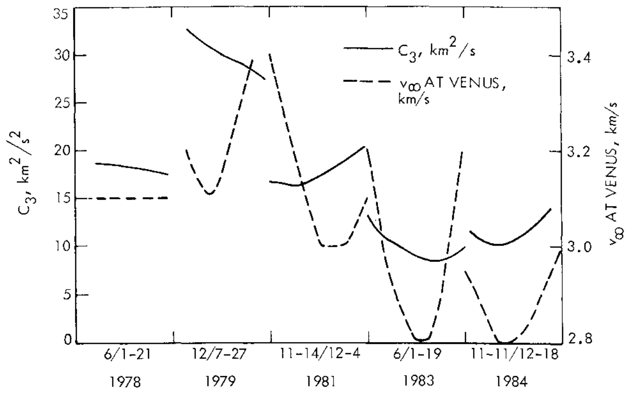

Fig. 5 VOIR mission performance summary.

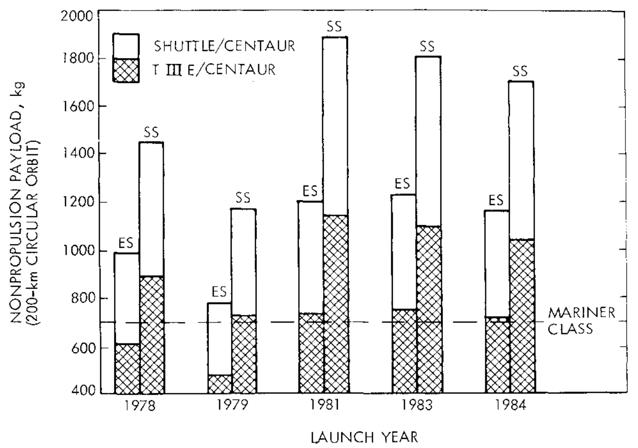

Fig. 6 VOIR payload delivery capability.

the capabilities of various orbit insertion systems, including conventional Earth-storable systems (similar to Mariner-Mars 1971 and Viking Mars 1975 propulsion systems) and high-energy, or space-storable, systems (bipropellant systems with a cryogenic oxidizer) which offer considerable I_{sp} performance increase over Earth-storable systems. An estimate of the payloads deliverable into a low, circular Venus orbit (200-km altitude) by each of the combination of launch vehicle/orbit insertion systems is shown in Fig. 6 for each opportunity. It may be seen that the Titan III E/Centaur/Earth-storable combination can deliver a typical Mariner payload for all but the first two opportunities, and a step up in either launch vehicle or propulsion system capability can meet all opportunities. For this reason it was decided to consider Titan III E/Centaur as the baseline launch vehicle and to determine later the tradeoff to make in orbit insertion capabilities. Availability of the shuttle launch will hopefully provide an increase in the available performance.

C. Baseline Mission

Launch year

The 1981 opportunity was chosen as the baseline for two reasons: 1) it is representative of all the opportunities and is not the easiest in terms of deliverability; 2) the time frame is compatible with the Venus science strategy discussed earlier. Table 1 outlines the baseline mission characteristics.

Venus orbit

The orbit selected is a 500-km altitude polar circular orbit which has the following characteristics and advantages: 1) the circular orbit minimizes the radar doppler shift requirements by minimizing the Venus-radial component of spacecraft velocity; 2) the altitude is low, and hence eases the radar design requirements, without encountering undue navigation and atmospheric uncertainties (a more extensive analysis is required to justify any significant further reduction in altitude); 3) the polar orbit allows complete planet mapping without 120 days.

Table 1 VOIR baseline mission parameters

Launch window	Nov. 14, 1981 to Dec. 4, 1981	
Arrival window	Mar. 13, 1982 to Mar.23, 1982	
C_3 (km²/s²)	16.60 to 20.4	
V_{hp} km/sec	3.40 to 3.3	
$\Delta V(VOI)$,km/sec (impulsive)	3.53 to 3.4	
Orbital mission duration, days	120	
Orbital altitude, km	500	
Orbital inclination	Polar	
	VOI	VOI + 120 days
Venus/Earth distance, GM	81	210
Earth/spacecraft/sun angle, deg	102	44
Canopus/spacecraft/sun angle, deg	84	96

The occultations of sun and Earth have a major impact on the design of the mission. For a circular orbit at low altitude, maximum sun and Earth occulation periods of up to 40% of the orbital period occur on cycles of 120- and 160-day centers, respectively, and more than 90% of the spacecraft revolutions about Venus encounter either sun or Earth occultations or both.

D. Data Strategy

The data strategy ground rules are derived from the science requirements for mapping coverage and resolution. Since the revolution-to-revolution shift of spacecraft ground trace (†2 km at the equator) is much smaller than the typical radar swath width, and the radar system much prefers to be "locked" and mapping for an entire revolution, the strategy of mapping every N revolutions (where $N \approx SW/12$) can accomplish the objectives in half a Venusian rotation period. The remaining (N-1) revolutions can be used for other science or for data telemetry purposes. Two additional factors encourage this approach: 1) planet profiling, or altimetry in the imaging mode, is desired as a complement to mapping; 2) data telemetry link rates available are not sufficient to transmit the high-resolution data rates in real time, and hence a data storage/playback scheme will be necessary.

For the VOIR mission, a swath width ~ 100 km results in a value of $N=7$ or $N=8$ being appropriate with overlapping swaths being permitted. This means that 6 or 7 revolutions will be available for telemetry and profiling. The specific strategy chosen for this mission will be developed in the next section, along with the data rate requirements.

V. Spacecraft System Design

A. Data Requirements

The spacecraft data subsystem will be required to handle both the radar data rates input and the telecommunications rates output. All the data received from the radar in real time are recorded. After the data acquisition period, the recorded data are played back into the telemetry subsystem and transmitted to Earth. This allows the telemetry and radar functions to be combined in one high-gain steerable antenna and simplifies the operating modes.

Data acquisition and storage

Although the data are not acquired by the radar in an image format, but rather in a phase/time delay form, the amount of

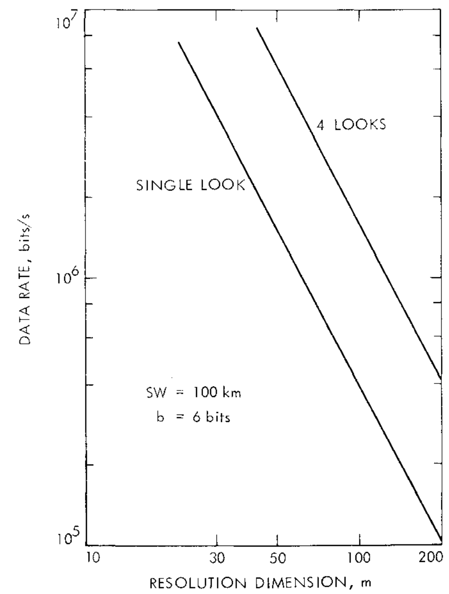

Fig. 7 VOIR data acquisition rate.

data acquired is approximately the same as for an equivalent image of the same resolution. This is not true if the system requires that multiple looks in range and/or azimuth be taken to provide acceptable radar signal-to-noise ratios. In that case, however, the data rate is that of the equivalent image multiplied by the number of looks required. For this study, 2 looks in range and 2 in azimuth are assumed. The problem of multiple looks has not yet been fully understood and is receiving attention; however, 4 looks are considered realistic at this stage.

The data rate required for an image of 6-bit digitized data with a resolution element u_am by u_rm is

$$B_0 \cong \frac{24(SW)v}{u_a u_r} \tag{9}$$

where SW and v are expressed in km and km/s respectively, B_0 in Mbits/s, and 4 looks are assumed. For the VOIR mission examined here, these data rates are shown in Fig. 7 for various resolution images (assume $u_a = u_r$). Figure 8 shows the data storage requirements for the onboard system for a single mapping swath at various resolutions (bottom) and the total data quantities acquired for a mission of 120 days (or complete planet coverage) at the same resolution (top), assuming an overlap at the equator of 31%, constant swath width and orbital velocity, and 6-bit digitization.

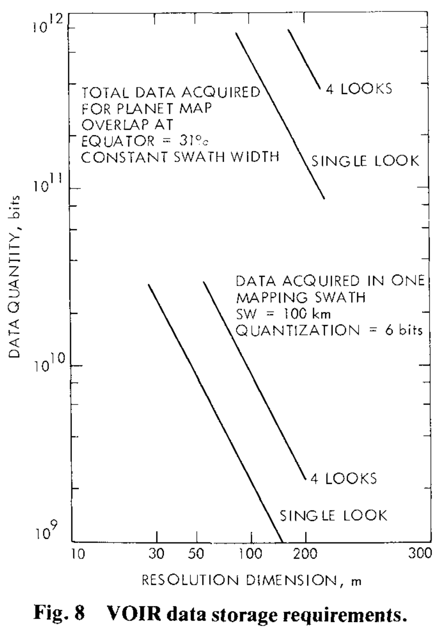

Fig. 8 VOIR data storage requirements.

Data telemetry

The $(N\text{-}1)$ orbits of the N-orbit mapping cycle can be used for data telemetry or other science. If we choose $N=7$ and further restrict the telecommunications link to a 0.5-Mbit/s data rate (see below), the number of data accumulation times required to play back the data at the maximum rate can easily be calculated. If, however, we include the requirement to obtain some data at high resolution, the determination of data parameters becomes more significant. Figure 9 shows the amount of high-resolution imagery of the planet surface available in a single mapping revolution and the amount of data storage required, as a function of the number of telemetry revolutions available at 0.5 Mbits/s. The capability drops when Earth occultation limits the telemetry time available.

B. Link Design

Ground Stations

The assumptions of *DSN* ground system capability in the 1981 time period were determined as they are projected for the Mariner Jupiter/Saturn 1977-era receiver/demodulation system operating at X-band. Although the station receiver bandwidth will be capable of handling up to 2×10^6 symbols/sec, the symbol synchronizer/demodulator capability will be limited to 0.5×10^6 symbols/sec without some modification. This was assumed as the upper symbol rate for this study.§

Spacecraft

The requirement for sharing telemetry and radar functions on a single circular parabolic dish was considered. To fit comfortably inside a Centaur launch shroud, a maximum diameter of about 3 m was acceptable which satisfied the radar *PRF* and antenna constraints previously discussed for a radar wavelength of 25 cm. This antenna provides a swath width of 107 km, which satisfies the data strategies considered. The telemetry performance of this system is shown in

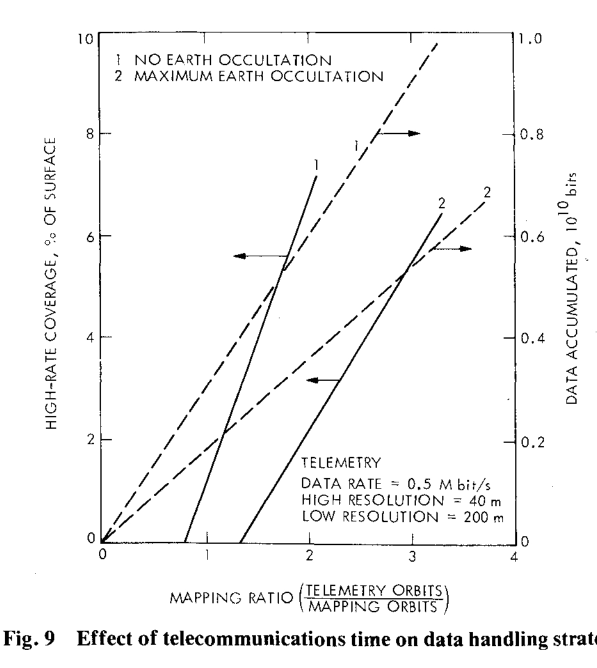

Fig. 9 Effect of telecommunications time on data handling strategy.

§Increasing this capability does not seem to be a major problem. A study is in progress.

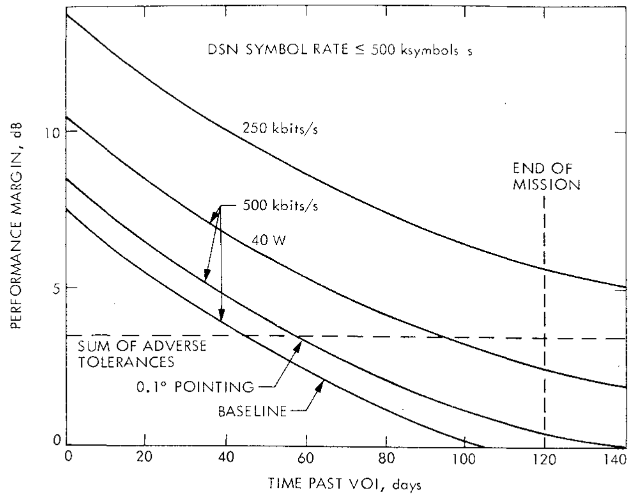

Fig. 10 VOIR high-rate telemetry performance.

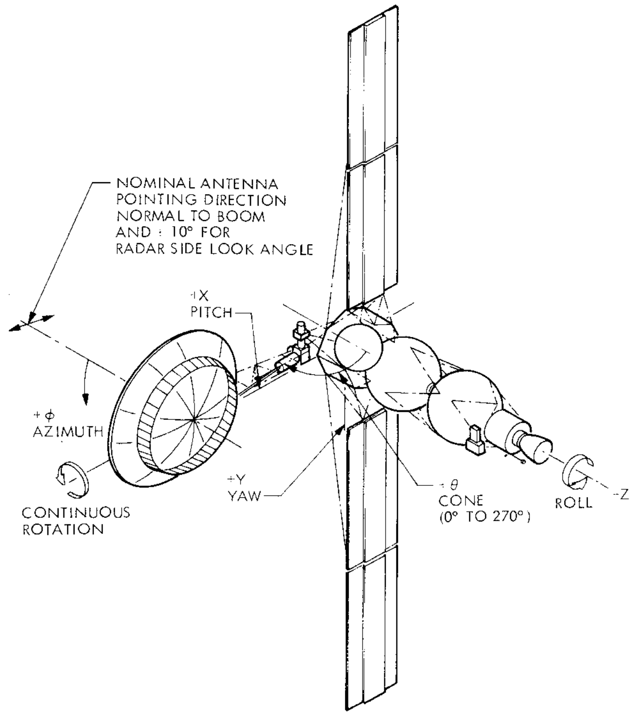

Fig. 12 VOIR spacecraft coordinate system.

Fig. 10 as a function of days in orbit. The analysis is based on the following assumption: 1) bit error rate of 5 × 10^{-3}; 2) station elevation angle of 25°; 3) one-way tracking, ranging off; 4) high-gain antenna (HGA) pointing accuracy of 0.25°; 5) 20-w x-band transmitter; 6) 500-kbits/sec uncoded science data stream. The effect of varying these parameters is also shown. It was thus determined that a favorable tradeoff of functions allowed the use of a single antenna for both radar and telemetry functions, providing that the rather exacting 0.25° pointing accuracy could be achieved.

C. System Support Design Requirements

Power

Having determined the radar antenna size, duty cycle, and signal-to-noise requirements, and using a representative system noise temperature, the required radar average transmitter power was determined. A power profile for a 7-orbit cycle is shown in Fig. 11. Three power levels are associated with radar off, radar on, and radar off with the antenna slewing at the high rate between radar data acquisition and data telemetry modes.

Two options for providing this power were considered. A solar panel power source is the most conventional lowest-cost approach, but requires a rather large battery system to provide power during sun eclipse. The subsequent battery charging period raises panel power requirements to ~900 w peak (Fig. 11). An *RTG* power source would eliminate the dependence on the sun, but is more costly. The power system design masses and configuration impacts were very similar for the two methods, and the better system for this mission will be determined later.

Configuration and temperature control

The spacecraft configuration is shown in Fig. 12. The orbital attitude of the spacecraft has the solar panels essentially north-south celestially and oriented toward the sun. The antenna boom for mapping is oriented perpendicular to the orbital plane, and the dish rotates about the boom 360° for a full imaging revolution. To accommodate the changing sun-orbit-Earth geometry, the antenna boom is articulated at the bus through 270°, folding down against the bus for launch and orbit insertion. The bus is mechanically and thermally of Mariner design, with each bay deepened by half again to admit the required electronics. A preliminary temperature analysis in the Venus orbit, using currently understood planetary albedos, indicates that the bus has the thermal capacity to radiate all excessive energy. The large propulsion tanks are arranged along the anti-sun line, a configuration compatible to both Earth-storable and cryogenic systems.

Attitude and articulation control

Definition of the Mariner-class spacecraft with a sun-Canopus celestial reference system poses some pointing control questions for both telecommunications and radar.

Fig. 11 VOIR power profile (7-orbit cycle).

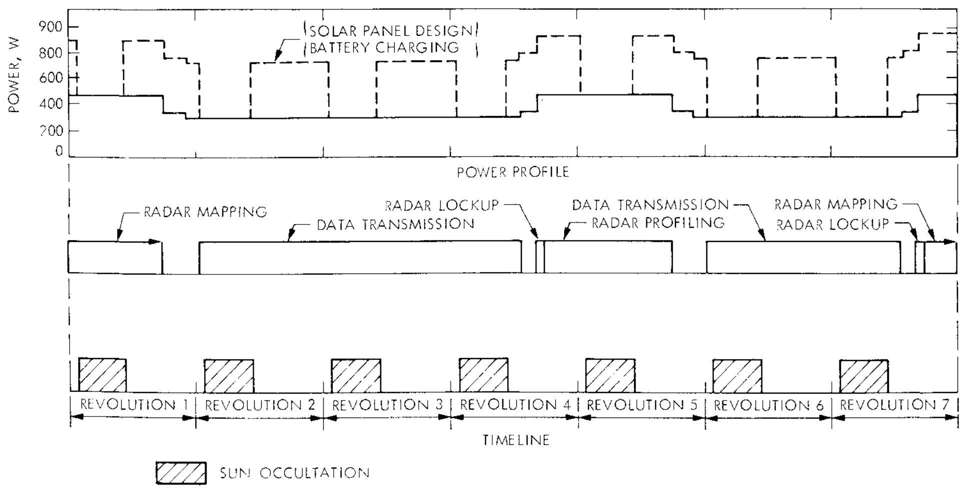

Table 2 VOIR baseline spacecraft mass summary

Subsystem	Mass, kg
Structures	195
Telecommunications	44
Attitude/articulation control	83
Bus support subsystems	112
Power	136
Data subsystems	46
Radar	47
Total (nonpropulsive)	663
Contingency (5%)	696

Table 3 VOIR propulsion system/launch vehicle performance summary

	Design mass, kg
In-orbit nonpropulsive mass	696
Propulsion system (+inerts, residuals)	425
Total in-orbit mass	1121
Usable propellant mass ($\Delta V = 3590$ m/sec)	2550
Spacecraft adaptor	53
Total injected mass	3724

Requirements of ± 4 mrad in absolute pointing knowledge were derived for both functions. The extreme dropoff in telecommunications performance with pointing misalignment of an X-band signal and a 3-m dish suggests the possibility of requiring an Earth sensor in the telemetry loop, although the baseline design did not include it. Pointing rate and position error requirements for radar stability exceed the capabilities of previous Mariner articulation systems. A servo loop consisting of hysteresis-synchronous motors, and an error signal derived from the doppler bias measured by the radar clutter-lock, are necessary to meet these requirements. Further analysis will shed more light both on the validity of the requirements and on more optimized solutions.

Orbit insertion propulsion

A major need in the baseline design was an advanced propulsion system to insert the nonpropulsion baseline design spacecraft mass into orbit. The preliminary conclusion, based upon the baseline design masses shown in Table 2a, was that an Earth-storable system could do the job. However, in some mission opportunities the payload margin is very small, or even negative, and hence a space-storable system would be of significant interest. A propulsion system with a dual-mode (bipropellant and monopropellant operation) capability and a 1000-lbf engine was chosen as being capable of minimizing orbit inserting burn losses with a large bipropellant engine and providing "fine-tuned" orbit adjustment capability in the monopropellant mode. The performance of the propulsion system under the assumption of a 20-day launch period, allowing off-loading of spacecraft propellants as window conditions require, is indicated in Table 3 for the worst-case condition occurring during the period (viz., the last day).

The impulsive ΔV on this day is 3400 m/sec. To this is added allowances for navigation and gravity burn loss so that a total of 3590 m/sec is to be provided. Gravity burn losses could amount to 400 m/sec if it were attempted to insert into Venus orbit in a single maneuver. Fortunately we can stage the retro maneuvers, inserting first into approximately a 10-hr orbit and then into the final orbit. The result is that gravity burn losses are kept to less than 3%.

Table 4 VOIR functional design features

Element	Baseline	Options
Power	Solar panel Batteries	RTG systems are cost effective and possibly need further study
Propulsion	Earth-storable orbit insertion 1000-lbf engine	Advanced (space-storable) systems are attractive for increased requirements
Telecommunications	0.5 Mbit/sec X-band science link	Data coding and updated DSN capabilities would make higher rates available (>1 Mbit/sec)
Attitude control	Sun/Canopus 3-axis control. Inertial control system for maneuvers, mapping mode	Alternate mechanizations need further study
Data	ERTS-type data storage system design	Alternate storage methods are not competitive at the time of this study Further assessment is required

The resulting total injected mass, from Table 3, of 3724 kg is within the range of planned Titan III E/Centaur capability. For $C_3 = 20.4$ km^2/sec,[2] the value of this last day in the launch vehicle capability is estimated as 3800 kg.

VI. Conclusions

Three major points were made in the VOIR study: 1) radar mapping of Venus is meaningful and important in the Venus exploration program; 2) a mission meeting all identifies science requirements could be undertaken at an advantageous time with existing launch vehicle capabilities; and 3) the spacecraft required to support the radar mission is feasible with current technology with some design features having several possible implenentation schemes (Table 4).

This paper has emphasized the third point and has discussed a nominal mission and spacecraft functional design, with a preliminary system and subsystem analysis of appropriate technology in support of the conclusion. Future Venus science assessments will change the scope of some of the tradeoff areas and will be the concern of future studies, which can hopefully use the results presented here as a starting point.

References

[1] Brown, W. E., et al., *Planetary Imaging Radar Study,* JPL Internal Document 701-145, June 1, 1972.

[2] Saunders, R. S., Friedman, L.D., and Thomson, T.W., *Mission Planning for Remote Exploration of the Surface of Venus,* AIAA Paper 73-580, Denver, Colo., 1973.