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VENUS RADAR MAPPER (VRM): MULTIMODE RADAR SYSTEM DESIGN

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I. INTRODUCTION

The surface of Venus has remained a relative mystery because of the very dense atmosphere that is opaque to visible radiation and, thus, normal photographic techniques used to explore the other terrestrial objects in the solar system are useless. The atmosphere is, however, almost transparent to radar waves and images of the surface have been produced via earth-based and orbital radars. The technique of obtaining radar images of a surface is variously called side looking radar, imaging radar, or synthetic aperture radar (SAR). The radar requires a moving platform in which the antenna is side looking. High resolution is obtained in the cross-track or range direction by conventional radar pulse encoding. In the along-track or azimuth direction, the resolution would normally be the real antenna beam width, but for the SAR case, a much longer antenna (or much sharper beam) is obtained by moving past a surface target as shown in Figure 1, and then combining the echoes from many pulses, by using the doppler data, to obtain the images.

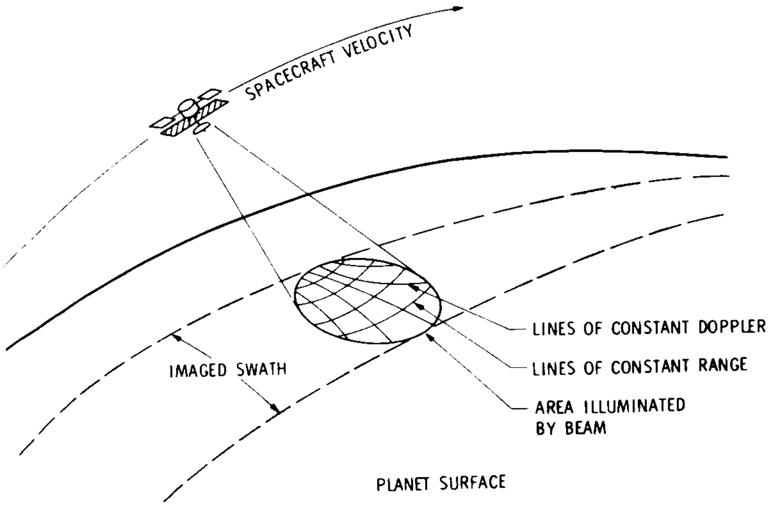


Figure 1. Radar imaging principle

The subject of this paper is the radar design of the Venus Radar Mapper (VRM) which is a United States National Aeronautics and Space Administration (NASA) planetary mission to be launched in 1988, that will acquire global radar imagery and altimetry data of the surface of Venus. The project is managed for NASA by the Jet Propulsion Laboratory (JPL) in Pasadena, California.

II. SCIENCE RATIONALE

Venus is the planet most like the Earth in the solar system. Great interest has been shown in it by both the U.S. and U.S.S.R.[1] In addition to Earth-based radar studies from the NASA Goldstone Deep Space Station, the U.S. has sent two missions, Pioneer Venus Orbiter and Pioneer Venus Multiprobe; and three fly-by missions, Mariners 2, 5, and 10, while the U.S.S.R. has sent several probes, orbiters, and landers: Veneras 4 to 16 and Vegas 1 and 2. The results of the surface imaging studies are summarized in Figure 2, along with the expected performance of the SAR portion of the VRM radar, while Figure 3 shows in more detail the VRM-SAR performance.

The science objectives of the VRM mission are: to improve the knowledge of the tectonics and geologic history of Venus by analysis of the surface morphology and the process that controls it; to improve the knowledge of the geophysics of Venus, principally its density distribution and dynamics; and to improve the knowledge of the small scale surface physics. To meet these objectives, the requirements on the radar system are: to produce contiguous images of at least 70% of the planetary surface with a radar resolution better than 300m; to produce surface brightness temperature measurements of the imaged areas at a temperature resolution better than 2°K; and to produce topographic and scattering characteristics maps with a height resolution better than 30m.

III. MISSION CONSTRAINTS

A combination of factors led to the major mission constraints listed in Table 1[2] [3] [4] [5]. The elliptical orbit and small antenna (compared to Earth orbiting SAR's) are the most demanding constraints from a radar system design view. The requirement on the design was to meet all science objectives within the mission constraints. The design had to make very efficient use of each of the limited resources, especially data rate. The mission must also complete all its objectives in one Venusian year or 243 days.

Table 1. Mission constraints

1. Elliptical orbit with period 3.1 to 3.7 hr.
2. Periapsis altitude 250 to 300 km
3. Voyager antenna 3.7 m (shared with telecommunications)
4. Data record rate 806 kbps
5. Data volume per orbit 1700 Mbits
6. Data rate to earth: 270 kbps
7. No real-time or near real-time commanding
8. Low-cost mission operations
9. Use existing digital processor

The absence of real-time command capability and desire for a simple radar dictates the use of navigation capability to set the radar data collection parameters. The radar is commanded by the spacecraft from repetitive sequences stored in the command memory. These sequences are calculated from navigation predictions and uploaded to the spacecraft three times a week.

	1978	1983	1988
	Pioneer	Venera 15/16	VRM
Periapsis altitude (km)	200	1000	250
Apoapsis altitude (km)	67000	65000	7800
Period (hr)	24	24	3.2
Shift in track at equator (km)	157	157	20.9
Attitude control method	Spin	Gas	Momentum wheels
SAR antenna (m)		6 x 1.4 parabolic	3.7 Dish
Altimeter antenna (m)	0.38	1 parabolic	0.08 x 0.8 Horn
Polarization	Linear	Linear	HH
Transmitter type	Solid state	TWT	Solid state
Peak power (W)	20	80	350
SAR bandwidth (MH_z)	0.25	0.65	2.26
Radar frequency (GH_z, cm)	1, 75, 17	3, 75, 8	2, 38, 12
Swath width (km)	Variable	~120	20 - 25
SAR data rate to S/C (kbps)	Low	~70	750
Operating altitude (km)	200-4000	1000 - 2000	250 - 3500
Record capacity (bits)	-	$\sim 10^8$	2×10^9
Range resolution (m)	23,000 -	1000 - 2000	120 - 300
Azimuth resolution (m)	70,000	1000 - 3000	120
Looks	Many	4 - 10	4 - 25
Coverage (%)	92	25	95
Incidence angle (deg)	0 - 5	7 - 17	15 - 45

Figure 2. Comparison of Venus radar missions

Altitude (km)	Latitude (deg)	Incidence angle (deg)	Range res (m)	Azimuth res (m)	Looks No.
250	+10	46	120	120	5
400	+23, -3	42	125	120	6
600	+46, -26	36	135	120	7
1000	+62, -42	28	170	120	8
1750	+83, -63	19	250	120	9
2100	+90, -70	17	260	120	10

Figure 3. SAR performance

The sharing of the rigidly mounted high-gain antenna (HGA) means frequent turns of the spacecraft for mapping and communications with Earth, along with star sighting for navigation. This sequence is repeated each 186 minutes, as shown in Figure 4.

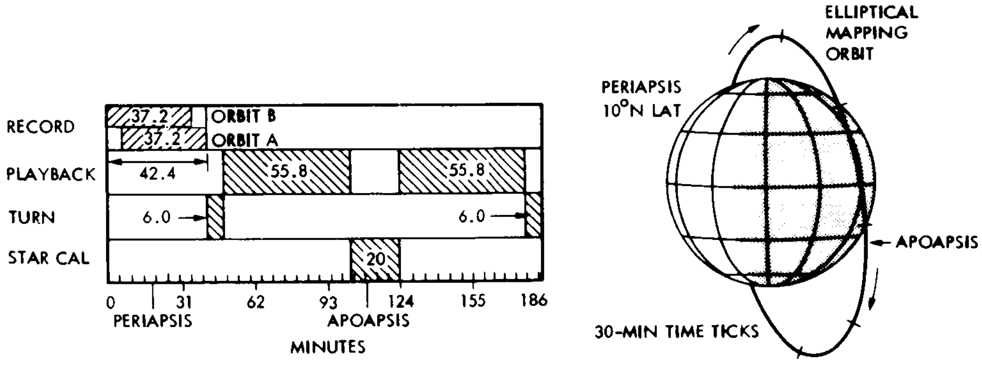


Figure 4. Mapping timeline and orbit geometry

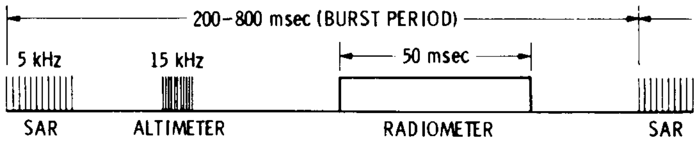
Because a great deal of redundant data is acquired near the poles, alternate passes are biased north (orbit A) or south (orbit B). The spacecraft accomplishes the turns with the required high accuracy through a three-axis stabilized gyro system. Even with all the turning, very little consumable liquid propellant is used which would limit the mission life.

The spacecraft including high-gain antenna, is an assembly of many parts from previous planetary missions, mainly Galileo and Voyager, while the radar is new, designed and built by Hughes Aircraft Corporation of El Segundo, California, under contract to JPL.

IV. SYSTEM DESIGN

The inherent high data rate of the SAR system must be reduced to satisfy the fixed data rate constraint imposed by the flight hardware. As shown in Figure 5, the radar employs a "burst mode" data collection scheme. The burst mode is a time domain data reduction method in which the transmitter is turned off periodically. The duration of the burst (i.e., the "on" time of the transmitter) determines the resolution, and the ratio of the burst period to the full operation duration determines the number of looks. This figure also shows the methods used to reduce the high instantaneous data rate. The echo is quantized initially to eight bits in two channels (inphase and quadrature) at the radar bandwidth of 2.26 MHz. This data is then passed through the Block Adaptive Quantizer (BAQ), discussed later, which reduces the data by a factor of four. The data is then buffered by the burst-on factor and sent at a constant rate to the spacecraft, which records the data. Later in the orbit, the recorded data is played back at a slower rate for transmission to Earth.

BURST MODE DATA COLLECTION PROCESS



INSTANTANEOUS DATA RATE (BITS / SAMPLE x CHANNELS x SAMPLE RATE)

$8 \times 2 \times 2.26 \times 10^6 = 36.2 \times 10^6$ BITS/SEC

USE BLOCK ADAPTIVE QUANTIZER (INSTANTANEOUS DATA RATE x BAQ FACTOR)

$36.2 \times 10^6 \times \frac{2}{8} = 9.05 \times 10^6$ BITS/SEC

BUFFER INTERPULSE AND BURST (REDUCED DATA RATE x BURST DUTY FACTOR)

$9.05 \times 10^6 \times 0.088 = 0.806 \times 10^6$ BITS/SEC

WITH 37.2 min RECORD AND 112 min PLAYBACK (AVERAGE RATE TO RECORDERS x RECORD TIME/ PLAYBACK TIME)

$0.806 \times 10^6 \times \frac{37.2}{112} = 0.268 \times 10^6$ BITS/SEC

Figure 5. Burst mode process and data rate calculation

The above reduction in data rate had to be accomplished without significant loss of image quality. SAR image quality can be described by five parameters: looks, spatial resolution, amplitude resolution, signal to noise ratio (SNR), and incidence angle. These parameters are not independent and a balance must be achieved to satisfy all these requirements within the mission constraints.

A. Looks

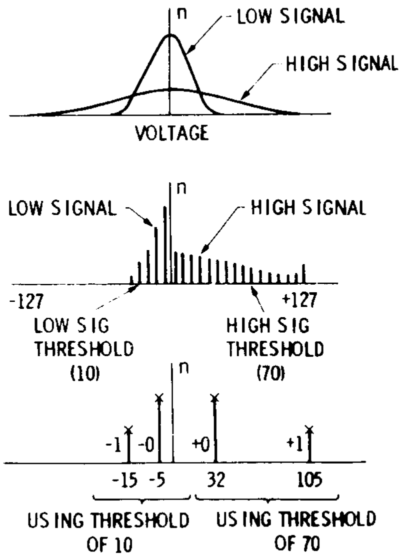
The "looks" in a SAR system are needed to reduce the coherent, or speckle, noise associated with images derived from coherently-illuminated sources. The looks are independent observations and are generally produced by frequency-domain filtering which reduces the azimuth resolution by a factor equal to the number of looks. For VRM SAR the looks are taken by using each burst of SAR data for a single look.

B. Spatial Resolution

The range (across-track) and azimuth (along-track) resolutions for a SAR are individually selectable, and both are independent of range to the target. The range resolution is determined by the transmitted bandwidth. The azimuth resolution is independent of radar bandwidth and is determined by the length of the "synthetic aperture" created while moving past a target.

C. Amplitude Resolution

The amplitude resolution of a SAR system is the ability to produce an output image with amplitude proportional to the radar backscatter coefficient of the surface. The system must have sufficient accuracy and dynamic range to satisfy rather stringent science requirements. A large dynamic range is associated with a large number of bits per sample, but since the data rate is of critical importance here, a new method was employed to achieve large dynamic range while using fewer bits, the "Block Adaptive Quantizer" (BAQ). This approach yields a larger dynamic range by first quantizing to a large (8) number of bits, and then selecting the most significant bits (2) for recording. The "significant bits" are determined through a block "threshold detector" which preserves a portion of the amplitude information in the original signal. The threshold information is combined with the selected bits in the ground processor to reconstruct the original data as accurately as possible. Figure 6 shows this process for low and high signals. One negative aspect of the BAQ and burst mode is the need for a memory in the radar of sufficient size to contain all the bits from one complete burst so that a constant rate of data is sent to the spacecraft recorders.



PROBABILITY DISTRIBUTION OF VOLTAGE INTO A/D

HISTOGRAM OF DIGITAL VALUES OUT OF A/D. (ONLY ONE SIDE SHOWN) THRESHOLD VALUES ARE ESTABLISHED BY PULSE AVERAGING AND TABLE LOOK UP IN THE RADAR

CONVERSION TO 2 BIT FORMAT IN WHICH VALUES BELOW THE THRESHOLD ARE CONVERTED TO 0 AND ABOVE 1. THE SIGNS ARE CARRIED THROUGH

THE EIGHT BIT FORMAT IS RECONSTRUCTED IN THE PROCESSOR BY MULTIPLYING THE 0's AND 1's BY 0.45 AND 1.5, RESPECTIVELY, TIMES THE THRESHOLD VALUE

Figure 6. Block adaptive quantizer operation

D. Signal to Noise Ratio

The thermal signal to noise ratio (SNR) for the system was chosen to be 8 dB based upon several simulation studies of images at various SNR's and quantization levels using real SAR data. For a 2-bit quantization level and more than four looks, higher values of thermal SNR were difficult to discern and lower values degraded the images. The system SNR which includes the sum of all noise contributors such as thermal noise, ambiguities, saturation and quantization noise, noise associated with the processor, and link error noise effects is about 5 dB in the output image.

V. RADAR SYSTEM

The radar system is comprised of the radar flight equipment, the radar data processing subsystem, and those elements in the Spacecraft Flight System, the Deep Space Network, and the JPL Mission Operations System that are involved in uplink command and control and downlink transmitting and recording of the radar data stream. The radar flight equipment consists of the sensor subsystem and the altimeter antenna subsystem. Figure 7 illustrates the spacecraft system and the radar system.

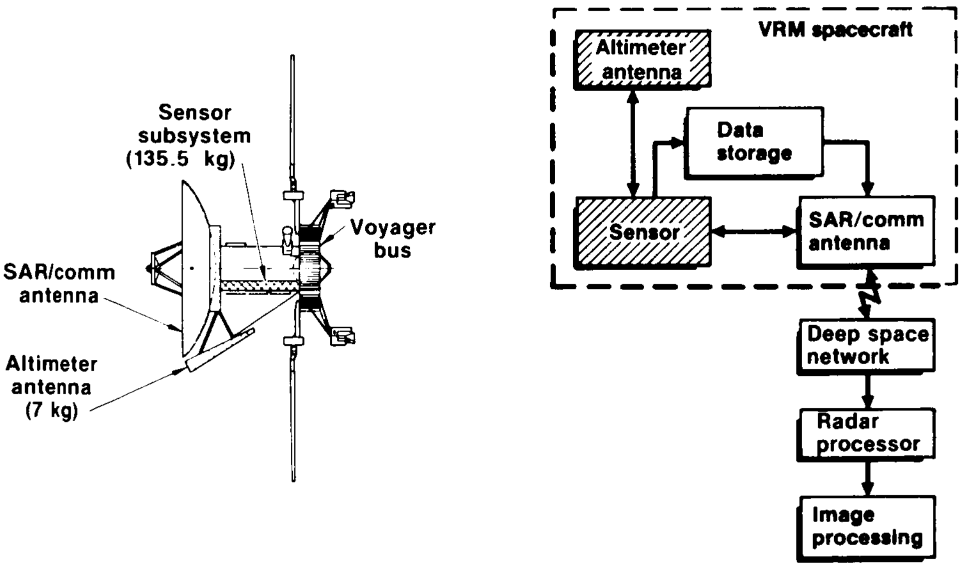


Figure 7. VRM radar system

The VRM spacecraft, a modified Voyager bus, transports the sensor subsystem and antennas along an interplanetary trajectory. It then inserts itself into a 3.2-hour, nearly polar, elliptical orbit around Venus, with a 250 km periapsis altitude at 10 deg north latitude. Mapping commands, generated on the ground, are relayed to the sensor subsystem by the spacecraft command and data subsystem. The sensor subsystem operates in a mapping mode up to an altitude of 2200 km (degraded operation to 3500 km) sending radar data containing SAR, altimeter, and passive radiometer data to the spacecraft tape recorders for storage. During the remainder of the orbit (near apoapsis), the spacecraft reorients itself toward Earth, and the radar data and engineering telemetry are transmitted to the Deep Space Network (DSN) via the same 3.7-meter parabolic high-gain antenna (HGA) used for mapping.

Preliminary ground processing removes overhead data added by the spacecraft, performs initial decoding, and provides the radar processor the radar data generated by the sensor subsystem along with ancillary data. The radar data are subsequently processed into image data records. The altimeter and radiometer data products are generated by the Multimission Image Processing Laboratory at JPL which also mosaics the image data records from each mapping pass into large maps.

A. Radar Flight Equipment

The sensor subsystem implementation blends many electronic domains including dc power conversion, microwave pulsed power, low noise microwave amplification, RF and video amplification, analog-to-digital conversion, coding, and digital data formatting, and employs many digital logic families including ECL, Schottky, low power Schottky, and CMOS. The sensor subsystem mounts to the spacecraft in one mechanical assembly. Subsystem electrical interfaces with the spacecraft include power, command, telemetry, radar transmission, RF digital reception, and the radar data stream.

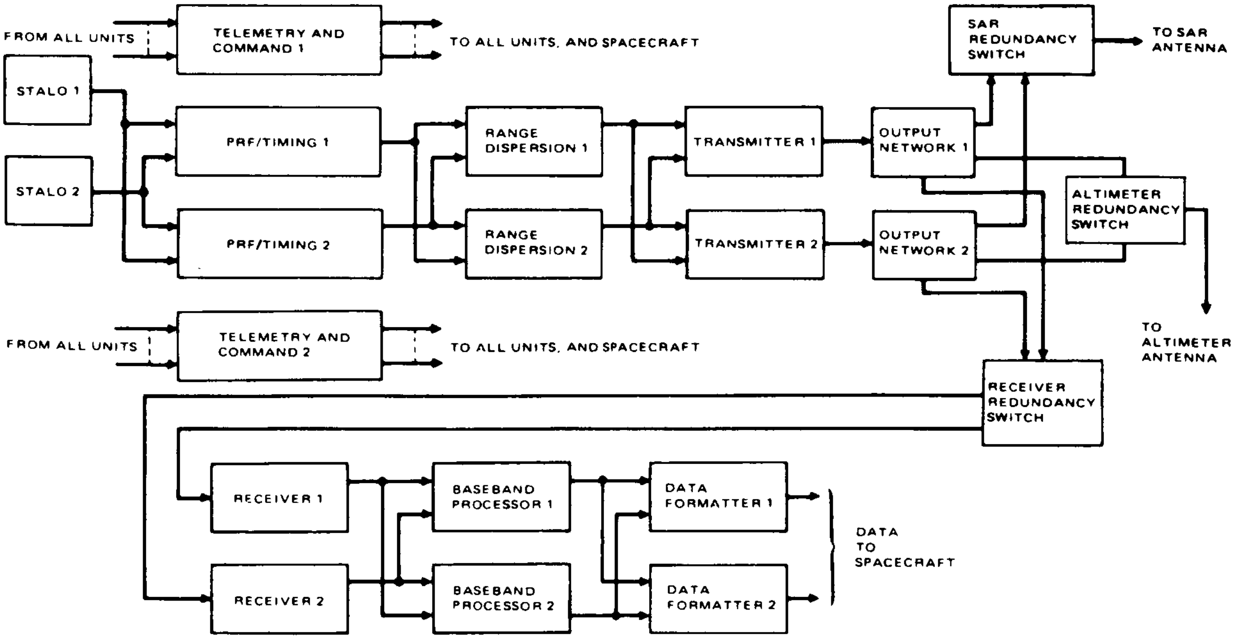


Figure 8. Sensor subsystem

The sensor subsystem is partitioned into the units shown in the Figure 8 functional diagram. Each unit has clearly defined elements grouped on the basis of similarity of function, electronic discipline, packaging efficiency, redundancy cross-strapping, and power consumption. The sensor subsystem is comprised of redundant, cross-strapped units which are separately testable. All circuit replacement is accomplished at the unit level. The unit functions are shown in Table 2.

Table 2. Unit functions

PRF and timing	Generate stable timing and clocks
Range dispersion	Generate coded S-band signal
Transmitter	Amplify S-band signal
Output network	Connect transmitter/antenna/receiver; monitor forward/reverse power
Receiver	Amplify low level echos and planet emission; provide first downconversion and gain control
Baseband processor	Provide downconversion and digitization to 8 bits
Data formatter	BAQ, buffer high-rate radar data and create radar data stream
Telemetry and command	Accept and execute spacecraft commands, time; process radar engineering telemetry

Units are packaged in one or more modules. A unit is defined to be nonredundant; thus two units of each function are flown in the sensor subsystem. Should a unit be removed from the sensor subsystem, the testing can continue using the remaining unit. An exception is the output network unit, which contains single antenna and receiver redundancy select switches. Subsystem test cannot proceed on a backup path if an output network module is removed. Figure 9 shows the sensor subsystem layout. The sensor subsystem mass is 137kg and draws 220 watts (average) during mapping. Sensor dimensions are 1.35m by 85cm by 33cm.

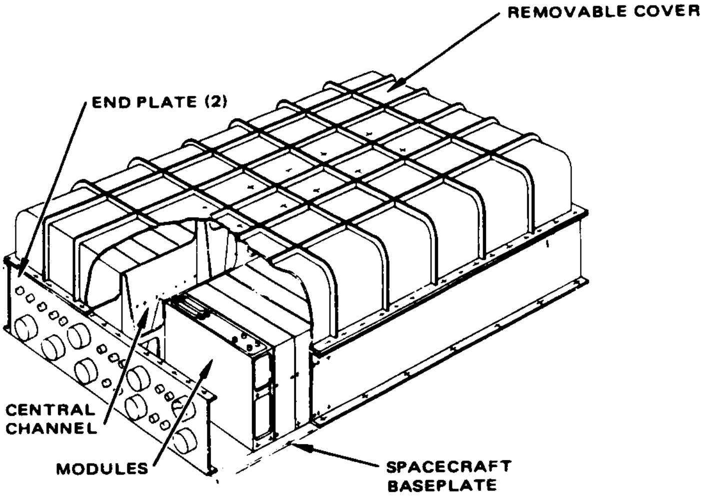


Figure 9. Sensor subsystem conceptual external view

The Stable Local Oscillator (STALO) is the heart of the subsystem. It is the source of all clocks and timing pulses used by the subsystem and serves as the input to the frequency synthesizer that produces the S-band carrier. The stability of the STALO is specified such that the entire system is coherent over a real aperture period. All clocks and timing signals are derived from the STALO by the PRF/Timing unit and distributed to the appropriate units.

The STALO frequency (72.27 MHz) is multiplied by 33 in the range dispersion unit, where a biphase code modulates the S-band carrier. The encoded S-band signal (2385 MHz) is gated into the transmitter, where it is amplified to a 350 watt peak power S-band pulse. The pulse is 26.5 μsec long and consists of a 60:1 code, each chip being .442 μsec. It is the chip time (bandwidth) that determines the radar range resolution.

There are two transmitter output ports, one to the altimeter antenna, the other to the HGA. When imaging, the output network connects the transmitter output to the HGA during the high-power transmit time and steers the target echo power captured by that antenna to the receiver. During the altimeter function, the output network connects the transmitter altimeter port to the altimeter antenna and directs the echo energy to the receiver.

The receiver, which has a high power switch to protect it from leakage during the transmit time, amplifies the S-band echo power and provides, by commandable gain control, the radar sensitivity. The echo information is then downconverted to IF and amplified further. A second downconverter in the baseband processor generates in-phase and quadrature signals, which are digitized after differentially accounting for the dc restore level. The resultant digital words are sent to the data formatter unit which rate buffers the data.

After combining the SAR imaging data with altimetry data, time tags, and format headers, the data formatter provides the data stream, which is clocked across the spacecraft interface in two parallel streams at a 403.2 Kbps rate each.

Within the telemetry and command unit, spacecraft commands are distributed by the command element and engineering data are digitized, buffered, and sent to the spacecraft by the telemetry element.

The sensor also collects radiometer samples every burst cycle, to obtain passive radiometric measurements of the planet's surface brightness temperature. PRF/Timing logic creates a radiometer sample gate and reset/dump signal, and adjusts the commandable receiver gain during the radiometer integration period. Within the receiver, a separate integrate-hold-dump circuit is provided for the radiometer samples.

Radiometer and calibration measurement samples are interleaved, with one or the other taken every burst. Calibration is normally accomplished by a radiometer measurement of the receiver protect switch. Occasionally, cold sky observations may be taken. Radiometric measurement data are digitized by a 12-bit A/D converter and sent to the data formatter, where they are included with the radar burst header.

VI.- DEVELOPMENT STATUS

Development models of the sensor and altimeter antenna subsystem are in test at this writing and construction of the flight model sensor subsystem is in process. These items will be completed and delivered to spacecraft integration in May 1986.

VII. CONCLUSIONS

The Venus Radar Mapper mission presents challenging radar design requirements which have been satisfied through the use of an existing Voyager antenna for the SAR function and newly developed sensor and altimeter antenna subsystems. The sensor uses a block adaptive quantizer to maximize science data return with minimum transmission of radar data back to earth.

ACKNOWLEDGMENTS

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