RADAR SYSTEM DESIGN FOR THE MAGELLAN RADAR

MISSION TO VENUS

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ABSTRACT

The Magellan Radar Mission to Venus will observe the planet at microwave frequencies in three simultaneous modes: a synthetic aperture radar (SAR or "imaging") mode, an altimeter mode, and a radiometer mode. Mission constraints require that the radar system operate from a highly elliptical orbit, for which there exists little previous flight experience. A multimode radar system has been designed to accommodate this new constraint. In addition, cost and data rate considerations prompted several novel approaches to subsystem design. The nominal mission will last one full Venusian rotation or 243 days. This paper will describe the science objectives, mission constraints, radar system design, flight hardware, and ground processing methods.

INTRODUCTION

To be launched in 1989, Magellan is a NASA planetary mission designed to acquire global radar imaging and altimetry data describing the surface of Venus. The Jet Propulsion Laboratory (JPL), the NASA center responsible for the mission, has contracts with Martin Marietta of Denver, Colorado, for the construction of the spacecraft; and with Hughes Aircraft Corporation of El Segundo, California for construction of the radar sensor, that is the entire scientific payload. A Venus gravity experiment will also be performed which will make use of the telecommunications link. In this paper we describe the system design of the radar, summarize the major scientific objectives, and discuss some of the significant mission constraints.

The Magellan radar system design is constrained by three requirements that have not been applicable to previous orbital imaging radar systems. First, and most important, operational considerations require that the radar operate from an elliptical orbit (Ref. 1). The Apollo Lunar Sounder, SEASAT, and Shuttle Imaging Radars (SIR-A and B) all operated from very nearly circular orbits so that there is little previous experience to draw upon for the present orbital geometry. The Pioneer Venus Radar Mapper operated from a highly elliptic orbit, but that instrument was primarily an altimeter. The USSR sent two orbiting SAR's to Venus in 1983 , Venera 15/16, which acquired data from a 24 hr elliptical orbit. Although these two instruments increased tremendously our knowledge about the Venusian surface they had much less demanding scientific objectives than Magellan for surface imaging.

Second, because of cost considerations, a single antenna must be used for both the synthetic aperture radar (SAR) and the telecommunications aspects of the mission. SAR designs generally require an antenna with very different characteristics than a telecommunications antenna.

A third, and somewhat less demanding constraint, is that, with the exception of the radar, much of the hardware must be inherited from past missions as a method of reducing costs. This form of cost reduction was applied to all other aspects of the mission, with the radar itself designed to minimize cost while maximizing the scientific content of the data. Thanks to this economy of design, the radar can operate concurrently in SAR, radiometer, and altimeter modes.

SCIENCE OBJECTIVES

The science objectives of the Magellan mission are: to improve the knowledge of the tectonics and geologic history of Venus by analysis of the surface morphology and the processes that control 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 500 m; to produce surface microwave brightness temperature measurements of the imaged area at a temperature resolution better than 2 deg; and to produce a topographic map with a height resolution better than 50 m.

MISSION CONSTRAINTS

Each of the major mission constraints has a profound impact on the radar design. These are listed in Table 1. We now discuss the effects of each of these constraints, and the various tradeoffs involved.

1. Elliptical Orbit with Period 3.1 to 3.3 hr.
2. Voyager Antenna 3.7 m (shared with telecomm)
3. Data Record Rate 806 kbps
4. Data Volume per Orbit 1700 Mbits
5. Data Rate to Earth: 270 kbps
6. No Real-Time or Near Real-Time Commanding
7. Low-Cost Mission Operations
8. Use Existing SAR Digital Processor

Table 1. Mission Constraints

Elliptical Orbit

Operational considerations for the Magellan mission constrain the orbit to a highly eccentric shape, varying greatly in altitude, and hence radar range. Assuming a nominal 3.15-hr. orbit period, as shown in Fig 1, with a 250-km periapsis altitude at 10 deg north latitude, the altitude will be approximately 2100 km at the north pole. The radar must operate over this range of altitudes on each orbit in order for most of the planet surface to be mapped in 243 days, one Venusian rotation. The swath width requirement is at least 20.5 km at the equator reducing to zero at the pole. The actual data swath width must be greater to allow for: i) pointing and altitude errors during data acquisition and, ii) overlap of swaths to facilitate putting the long, narrow strips together to form mosaicked images of large areas. From a system design point of view, it would be easier to design and operate a system that used a constant look angle since the spacecraft would merely have to pitch down during a mapping pass. However, for several reasons the constant look angle cannot be used for Magellan. Fortunately the spacecraft selected for the mission is gyro-stabilized and can be steered to any orientation with great accuracy. This pointing ability was a very important consideration in the system design.

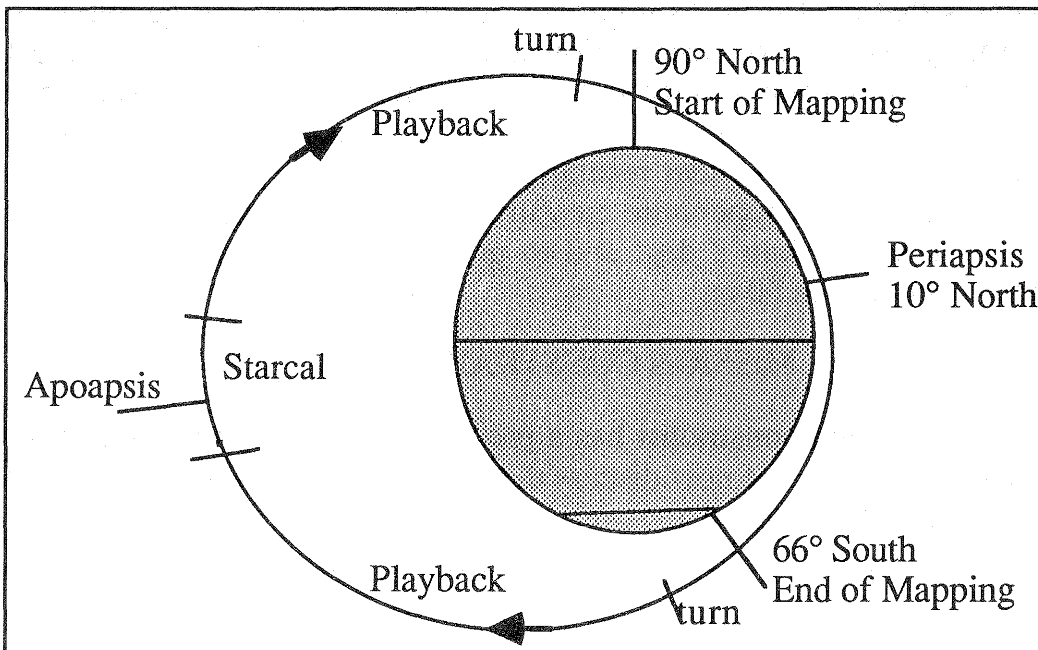

Fig 1. Orbit Sequence

Antennas

The mission cost constraints required that the system be designed around an existing antenna. The largest and hence highest gain antenna available was the spare 3.7 m-diameter parabolic reflector developed for the Voyager mission to the outer planets. This antenna, used for communication with the spacecraft, was originally built with two feeds, one for 3 cm wavelength the other for 13 cm wavelength transmissions. For Magellan, the 13 cm feed was modified for use by the SAR while the 3 cm system will be used for the high-rate data link.

This high gain antenna (HGA) is small by usual SAR standards, and, in addition, the circular aperture is not ideal for most SAR applications. A telecommunications antenna is optimized for gain with a broad beam, while an optimized SAR antenna usually has a narrow beamwidth in the direction parallel to the flight track and a broad beamwidth in the cross-track direction. The operation of a non-ideal antenna from a wide range of altitudes requires a compromise in system design at almost all altitudes; at low altitudes the antenna beam should be wide in range (cross-track) while at high altitude it should be narrow in range. The fixed beamwidth, thus, under-illuminates the swath at low altitude and over-illuminates the swath at high altitude.

The requirement to acquire simultaneous altimeter data would usually mean a separate, down-looking antenna and separate radar system. The low-cost constraint meant that the altimeter must share most of the radar electronics with the SAR, and that both the SAR and altimeter antennas would be fixed rigidly to the spacecraft, and therefore, be pointed by spacecraft movement. Optimization of the SAR data quality requires the look angle (cross-track angle measured from nadir) be varied as a function of altitude. Since the two antennas are fixed to the spacecraft, the altimeter antenna beam must be fan shaped so that a portion of the main beam is always nadir-pointing. The antenna constructed was a 150 cm horn with a fan shaped beam with dimensions 10° by 30°.

Data Rate and Volume

The constraint of a single antenna for SAR and telecommunication requires that all radar data must be recorded during a periapsis-centered, or mapping pass, and be played back later in that same orbit in order for the tape recorders to be free to record the next mapping pass. To achieve the objective of near total planetary coverage in one Venusian year, every orbit must be a mapping orbit. Thus, an orbit of approximately 189 minutes is divided into 37 min of radar data recording, 112 min of playback, and the balance for star sighting (attitude reference calibration) and spacecraft turns. The data volume on the recorders is 1800 Mbits of which 1700 Mbits are available to the radar. The record rate is 806 kbps of which 790 kbps is radar with the remaining portion for spacecraft engineering and formatting. The design must use the available 790 kbps in the most efficient manner to satisfy the science requirements.

Radar Commanding from the Spacecraft

Simplification of the radar flight hardware requires the use of the existing, sophisticated commanding capability of the inherited Galileo command and data system (CDS). Thus, the radar will accept all of its commands for operation from the spacecraft CDS. The CDS will generate the commands using a sequence list in its memory. The pointing of the HGA is also controlled by the spacecraft in the attitude control system. The CDS and attitude control system work totally from data memory that is updated from the ground (Earth) via the deep space net (DSN) from JPL. For the radar operation a set of time tagged commands are loaded into memory for execution during each mapping pass. These commands are generated on the ground, based upon predictions of the location of the spacecraft which are derived from the navigation data analyzed at JPL. In order to generate this command list and operate the radar system in an efficient and optimized manner a set of computer programs were written called the Radar Mapping Sequencing Software (RMSS). Very accurate navigation information is required to operate the radar in this manner as the radar and spacecraft have no ability to modify the commands based upon onboard information. This method of commanding is called "open loop". After the data is processed, refinements can be made to the command list through the use of RMSS to optimize the data collection process.

Mission Operations

The mission operations cost constraints meant that there could not be 24 hour per day staffing for the operation of the radar. The relatively long period of the mission, about eight months after orbit insertion, meant a considerable savings in team size and expenses of training and operation. The radar will operate on navigation predictions of orbit position that will be made only three times a week (Monday, Tuesday, and Friday). The radar system accommodated this method of operation by increasing the data swath to accept larger altitude and pointing errors than those that would occur if the updates were more frequent. The effect is a loss in radar data quality and more redundant coverage than might otherwise be necessary.

Radar Data Processing System

The SAR data, and less so the altimetry data, require extensive processing (called correlation) before the data is in a useful form. The two methods of processing SAR data are optical (using lasers and lenses) and digital (using computers). The optical method has been used extensively in the past for both aircraft systems and orbiting SAR's, including SEASAT and SIR-A. It is a fast method of processing a large amount of data, but the resulting images are inferior in quality to the digitally processed products. Digital processors have been used to process substantial portions of SAR data from the SIR-B mission and aircraft SAR's. JPL has constructed an advanced digital SAR processor (ADSP) which will be capable of processing very large data sets. It will operate about 150 times faster than the present processor at JPL. The ADSP was developed for use by several space shuttle radar missions, including SIR-C which will be launched in 1991. The Magellan project will modify this processor and use it as part of a radar data processing system which will turn the raw SAR data into maps of the Venusian surface. The altimeter data is processed to yield a global topography map.

RADAR DESIGN

SAR image quality can be described by at least 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 the requirements. Other parameters such as wavelength, aspect angle, and polarization are also important but were not variables in the design due to other considerations.

Looks

The "looks" in a SAR system are needed to reduce the coherent, or speckle, noise associated with images of coherently illuminated scenes. 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. A minimum of four-looks was selected for all data and with a further requirement that if the data were processed to 300-m resolution in both range and azimuth, the number of "equivalent" looks would be at least 16.

Spatial Resolution

The range (across-track) and azimuth (along-track) resolutions for a SAR are individually selectable, although both are independent of range to the target for a continuous mode SAR. The range resolution is determined by the transmitted bandwidth, which corresponds to the so-called slant range resolution. When projected onto the planet surface this gives the surface range resolution. The azimuth resolution is independent of radar bandwidth and is determined by the length of the "synthetic aperture" created while moving past a target. The azimuth resolution can, in principle, be as small as about half the antenna length.

In order to create a balance between looks and resolution and also reduce the data rate, a special form of SAR operation has been developed called "burst mode". This technique creates a synthetic aperture of sufficient length to achieve the required azimuth resolution while reducing the number of pulses that would be required to be transmitted in a continuous-mode SAR. The burst duty cycle varies from about 10% at low altitudes to about 30% at high altitudes. In burst mode the azimuth resolution is a function of slant range to the target and, thus, the burst on-time must be increased as the altitude increases to maintain the same resolution.

The radar bandwidth selected is 2.26 MHz, which gives a range resolution of about 120 m at the low altitudes. The azimuth resolution was held at 120 m for all altitudes by varying the burst on-time.

Amplitude Resolution

The amplitude resolution of a SAR system is its ability to produce an image with output proportional to the backscatter strength of the surface. The system must have sufficient accuracy and dynamic range to satisfy rather stringent science requirements. As a large dynamic range is associated with a large number of bits per sample, and since the data rate is of critical importance here, a new method was employed to achieve large dynamic range while using fewer bits. The device is called the "Block Adaptive Quantizer" (BAQ) and is incorporated in the radar flight hardware. This approach yields a larger dynamic range by first quantizing to a large number of bits, and then adaptively selecting fewer bits for recording. The bits selected are determined by an averaging method that can change the encoding table as frequently as 24 times within each sampling window. The same set of 24 encoding tables is used for the corresponding segments of each echo in a burst, thus saving a considerable amount in data rate. This method of data reduction works well for radar echoes from the ground since the shape of each radar echo is nearly the same for each echo within a burst. The performance characteristics of this method has been proved through the use of real SAR data.

One negative aspect of the 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. The encoding table information is combined with the selected bits in the ground processor to reconstruct the original data as accurately as possible. For Magellan the data is originally quantized to eight bits, two of which are recorded. The burst buffer memory is 704 kbits.

Signal to Noise Ratio

The required 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 than 8 dB were difficult to discern and lower values degraded the images. The system SNR includes the sum of all noise contributors, such as thermal noise, ambiguities, quantization noise, noise associated with the processor, and link error noise. The system SNR is about 5 dB in the output image.

Incidence Angle

The incidence angle is the angle between the radar beam and the normal to the surface. For a surface with no slope this angle is equal to the radar "look" angle plus an increment due to the planet's spherical shape. The "ideal" angle of incidence depends upon the type of surface being viewed. For gently rolling terrains and oceans an angle from 20° to 30° is considered optimum. For most geologically interesting surfaces angles from 30° to 60° are best. As the incidence angle approaches 90°, the resulting SAR image appears more like an overhead photograph. Angles greater than 60° are very difficult to achieve with SAR due to low backscatter, shadowing, and the need for a very large antenna. Because Venus will likely have many geologically interesting areas, the angle of incidence was kept as large as possible for all altitudes. More than 70% of the returned data will be from areas for which the angle of incidence is greater than 30°.

RADAR FLIGHT HARDWARE

In addition to the antennas, the radar comprises a single box of flight hardware containing the following units: a stable local oscillator (STALO), PRF/timing, range dispersion, transmitter, output network, receiver, baseband processor, data formatter, and telemetry and command (Ref 2). Each unit is duplicated for redundancy with switching between units by ground command. The single box weighs about 150 kg and consumes about 200 W. The power is obtained from the spacecraft power system which uses batteries recharged from solar arrays.

The STALO is the source of all timing signals throughout the units which are sent from the PRF/timing unit. The telemetry and command unit accepts commands from the spacecraft and translates them into signals to the various modules. The range dispersion unit encodes a 26.5-μsec length pulse that is bi-phase modulated by a digital code of length 60. The transmitter amplifies this encoded signal to 350-W peak power. The output network directs the output to either the SAR or altimeter antenna and the echoes to the receiver where they are amplified and bandwidth limited to 10 MHz. The passive microwave radiometer measurements are made at this point. The baseband processor bandwidth limits the signal, decomposes the signal into inphase and quadrature (I&Q) components and quantizes each component to eight bits. The data formatter, that includes the BAQ, selects two bits from each eight bit word for buffering, adds the headers, with various set up and operational information encoded, and prepares the data for transmission to the spacecraft where it is recorded. The sample window is also set in the data formatter. The altimeter data follows much of the same path except that the data recorded are the four most significant bits (MSB's) of each eight bits without use of the BAQ. Each unit has a self contained power supply.

RADAR PERFORMANCE

The radar operates as shown in Fig. 2 in the SAR, altimeter, and radiometer modes in sequence every "burst period". The burst period is from 200 to 800 msec, depending on the altitude. It begins with a SAR burst of duration from 25 to 200 msec with a pulse repetition frequency (PRF) from 4400 to 5800 Hz. This is followed by a 1 msec altimeter burst at 15-kHz PRF and a 50-msec long radiometer receive-only interval. The SAR echoes are interleaved with the transmit pulses, as illustrated, while the altimeter echoes are received after the end of altimeter pulse transmission allowing for a simple, noninterleaved reception of altimeter echoes. The PRF and data window position for echo reception of the SAR signals are precisely controlled by frequent change commands from the spacecraft. These commands are calculated with the RMSS computer programs based upon altitude predictions as a function of time and are loaded from the ground rather than being spacecraft or radar echo derived.

The following set of calculations illustrates the manner in which the burst mode method of operation and the use of the BAQ combine to reduce the data from the instantaneous rate of 36.2 Mbps in the radar to the 270 kbps down link rate to the receiving station.

Instantaneous Rate: 2.26 MHz x 2 samples x 8 bits/sample = 36.2 Mbps

Average per PRF: 36.2 Mbps x 145 μsec data window/191 μsec interpulse period = 27.5 Mbps

Average Over Burst: 27.5 Mbps x 26.4 msec burst on-time/ 242 msec burst period = 3.00 Mbps

Use Block Adaptive Quantizer: 3.00 Mbps x 2 bits out/8 bits in = .75 Mbps

Add Altimeter and Headers: .75 Mbps + .06 Mbps = .81 Mbps

Playback Data: .81 Mbps x 37 min record/112 min playback = .27 Mbps.

As the altitude and look angle change the "Average per PRF" and burst on-time/burst period ratio each change, but the "Average Over Burst" rate remains 3.00 Mbps.

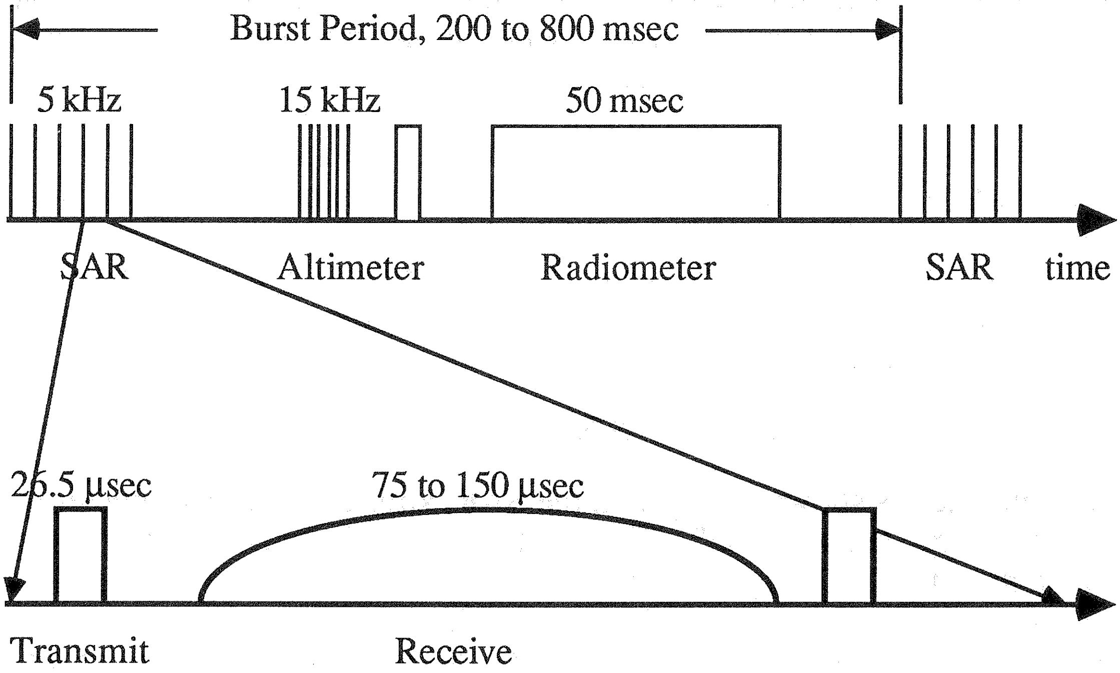

Fig 2. Burst Mode Data Collection

The use of a single antenna requires an elliptical orbit for a long playback time between mapping passes. A higher radar data rate would require a higher playback rate or longer period. In the Magellan mission design, the various elements that can be varied have been optimized to increase the quality and quantity of science data.

Table 2 shows the performance of the SAR as a function of altitude. This is only an example of how the radar might operate as many of the parameters such as look angle and burst parameters can be altered even when in orbit around Venus.

CONCLUSIONS

The Magellan radar system employs several unique data collection methods to obtain global images, altimetry data, and radiometry of the surface of the planet Venus. The unusual mission requirements for an imaging radar mission require interesting radar system design considerations to meet the science objectives. The design meets these objectives and will add a large data base for the science community to study Venus for many years after the mission's conclusion.

Altitude (km)	Incidence Angle (deg)	Range Res (m)	Azimuth Res (m)	Looks
250	50	115	120	5
275	48	120	120	6
500	40	135	120	7
1000	31	170	120	8
1750	20	260	120	12
2100	17	300	120	16

Table 2. SAR Performance

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