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Fact Sheet for the Chairman, Subcommittee on Science, Technology, and Space, Committee on Commerce, Science, and Transportation, U.S. Senate

May 1988

SPACE EXPLORATION

Cost, Schedule, and Performance of NASA's Magellan Mission to Venus

GAO/NSIAD-88-130FS

GAO

United States
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National Security and
International Affairs Division

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May 27, 1988

The Honorable Donald W. Riegle, Jr.
Chairman, Subcommittee on Science,
Technology, and Space
Committee on Commerce, Science, and
Transportation
United States Senate

Dear Mr. Chairman:

You asked us to assess the cost, schedule, performance, and status of the National Aeronautics and Space Administration's (NASA's)

-- Galileo mission to Jupiter;

-- Ulysses mission to the sun, a joint project with the European Space Agency;

-- Magellan mission to Venus; and

-- Mars Observer mission.

This report provides the requested information on the Magellan mission to Venus. We are issuing separate reports[1] on the other deep space missions. In addition, the overall results of our work, including the causes and impacts of delays and other issues related to the projects, are discussed in our report, Space Exploration: NASA's Deep Space Missions Are Experiencing Long Delays (GAO/NSIAD-88-128BR, May 27, 1988).

The Magellan mission is intended to investigate the origin and evolution of Venus. At the start of the project in fiscal year 1984, NASA estimated the project's total cost

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[1] Space Exploration: Cost, Schedule, and Performance of NASA's Galileo Mission to Jupiter (GAO/NSIAD-88-138FS, May 27, 1988); Space Exploration: Cost, Schedule, and Performance of NASA's Ulysses Mission to the Sun (GAO/NSIAD-88-129FS, May 27, 1988); Space Exploration: Cost, Schedule, and Performance of NASA's Mars Observer Mission, (GAO/NSIAD-88-137FS, May 27, 1988).

at $294.6 million, assuming that the spacecraft would be launched by the Shuttle in April 1988 and would use a Centaur upper stage to provide propulsion into an interplanetary trajectory. In October 1987, the mission cost estimate was increased about $219 million to $513.5 million, which was a result of launch delays adopting to a new upper stage, accommodating a new trajectory, and problems with the development of the mission's major scientific instrument.

The launch date for this mission was originally set for April 1988, and it was scheduled to end in April 1989. Since then, the launch date has changed twice. First, after the <u>Challenger</u> accident, the launch was moved back to October 1989. Second, the launch date was pushed forward to April 1989 so the Galileo spacecraft could be launched in October 1989. The new launch date for the Magellan mission requires the use of a longer trajectory that will delay the arrival of the spacecraft at Venus to August 1990, just over 2 years later than the originally planned July 1988 arrival date. The launch delay and cruise time increase has also delayed the end of the mission by 2 years to the end of April 1991. According to project staff, this mission's objective to map at least 70 percent of the Venus' surface is expected to be achieved.

As requested, we did not obtain official agency comments on this report; however, we discussed the report with NASA and Jet Propulsion Laboratory officials, and they agreed with the facts as presented. The objectives, scope, and methodology of our work are discussed in appendix I. A glossary of technical terms follows the project chronology in appendix II.

Unless you publicly announce its contents earlier, we plan no further distribution of this report until 10 days from its issue date. At that time, copies will be sent to other interested parties upon request.

If we can be of further assistance, please contact me on 275-4268.

Sincerely yours,

Harry R. Finley

Harry R. Finley
Senior Associate Director

Contents

ABBREVIATIONS

IUS	Inertial Upper Stage
JPL	Jet Propulsion Laboratory
MO&DA	Mission operations and data analysis
NASA	National Aeronautics and Space Administration
SAR	Synthetic Aperture Radar
VOIR	Venus Orbiting Imaging Radar
VRM	Venus Radar Mapper

MAGELLAN MISSION TO VENUS

The Magellan mission to Venus was originally designated as the Venus Orbiting Imaging Radar (VOIR). As first envisioned in 1980, the VOIR spacecraft was to carry a high-resolution Synthetic Aperture Radar (SAR) and six other instruments, most of them for atmospheric studies. The estimated cost for the VOIR mission was between $545 million and $635 million based on a fiscal year 1982 starting date.

After the VOIR funding was deleted from NASA's fiscal year 1982 and 1983 budgets, the National Aeronautics and Space Administration (NASA) dropped the atmospheric studies, lowered the SAR mapping resolution,[2] delete the aerobraking shield (which would have been used to propel the Shuttle Centaur into Venus orbit), and announced a "new project start" for fiscal year 1984--the Venus Radar Mapper (VRM)--at an estimated cost of $294.6 million. To keep the VRM mission within its budget, NASA opted to use existing spacecraft designs and technology and residual hardware, especially parts from the Galileo and Voyager projects.

VRM--renamed Magellan--is managed for NASA by the Jet Propulsion Laboratory (JPL). The spacecraft contract was won by Martin Marietta Corporation, and the Hughes Aircraft Company was awarded the SAR contract.

The primary objective of this mission is to investigate the origin and evolution of Venus by obtaining a global radar image of the planet. The surface of Venus has remained relatively unknown, since the photographic techniques used to image other planets are useless when imaging a planet shrouded in a dense atmosphere that is opaque to visible radiation. The SAR is designed to penetrate the opaque atmosphere of Venus.

This mission was originally to be launched in April 1988 on a direct ballistic trajectory by the Shuttle/Centaur upper stage. After the Challenger accident, the launch date was moved to April 1989, and the Centaur upper stage, which NASA canceled as a shuttle safety-related measure, was replaced by an Inertial Upper

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[2]The initial SAR objective was to map the planet with a radar resolution of 300 meters and to produce topographic maps with a resolution of 30 meters. It was lowered to 1,000 meters (1 kilometer) and 50 meters, respectively.

Stage (IUS). NASA then initiated studies of alternative launcher/upper stage combinations to replace the cancelled Shuttle/Centaur and to satisfy Magellan's launch energy requirements. In October 1986, NASA selected a Shuttle/IUS combination.

The April 1989 launch will use a longer trajectory, which extends the cruise time--the amount of time it would take a spacecraft to reach its destination--by almost 1 year. The spacecraft is scheduled to arrive at Venus in August 1990, and mapping of the planet is scheduled to be completed by April 1991.

The spacecraft will perform two types of investigations: radar and gravity. The radar investigations will produce (1) contiguous images of at least 70% (with a goal of 90%) of the planet with no systematic gaps except for one pole and with a surface resolution of at least 1 kilometer and (2) a global topographic map with a range of resolution commensurate with the SAR range of resolution. The gravity investigation will measure the distribution of gravity potential around Venus.

The mission is intended to improve knowledge of the tectonic and geological history of Venus through analyses of surface morphology density distribution and interior dynamics, and small-scale surface characteristics.

The scientific data gathered by the spacecraft will be used to determine the geological history and evolution of Venus. For example, some of the scientific information gathered could indicate volcanic processes and planetary thermal evolution; craters, which provide a means for obtaining the age of the surface; and geological formations, which add to evidence of ancient oceans. The gravity data to be obtained could be used to develop models of the density and stress within the interior of Venus.

OBJECTIVES, SCOPE, AND METHODOLOGY

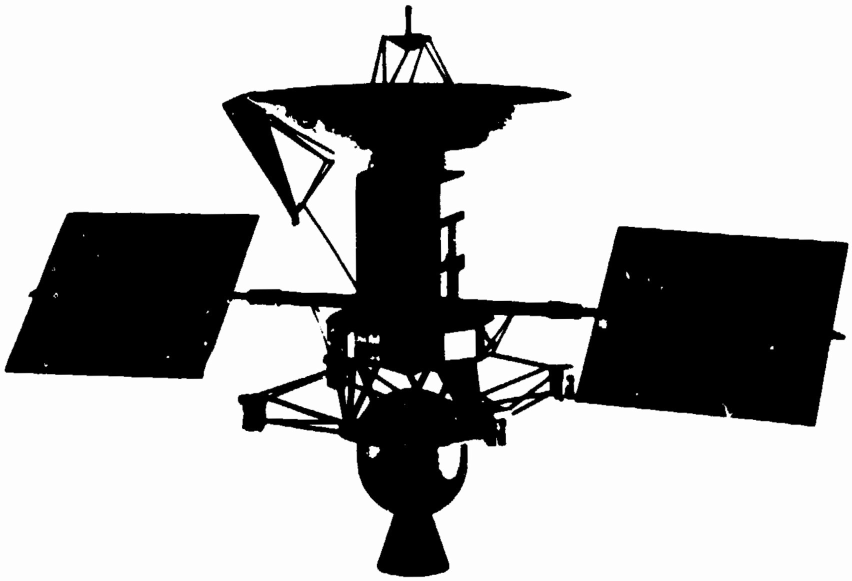
Our objectives were to describe this mission and obtain information on its cost, schedule, and performance. To accomplish these objectives, we interviewed NASA and JPL program and project managers responsible for the mission's design, development, and management. We also reviewed project planning and budget documents, articles in scientific journals, and reports in technical and trade periodicals. Our work was performed at NASA Headquarters in Washington, D.C., and at JPL in Pasadena, California. A more detailed description of our objectives, scope, and methodology on this assignment is contained in appendix I of our report, Space Exploration: NASA's Deep Space Missions Are Experiencing Long Delays (GAO/NSIAD-88-128BR, May 27, 1988).

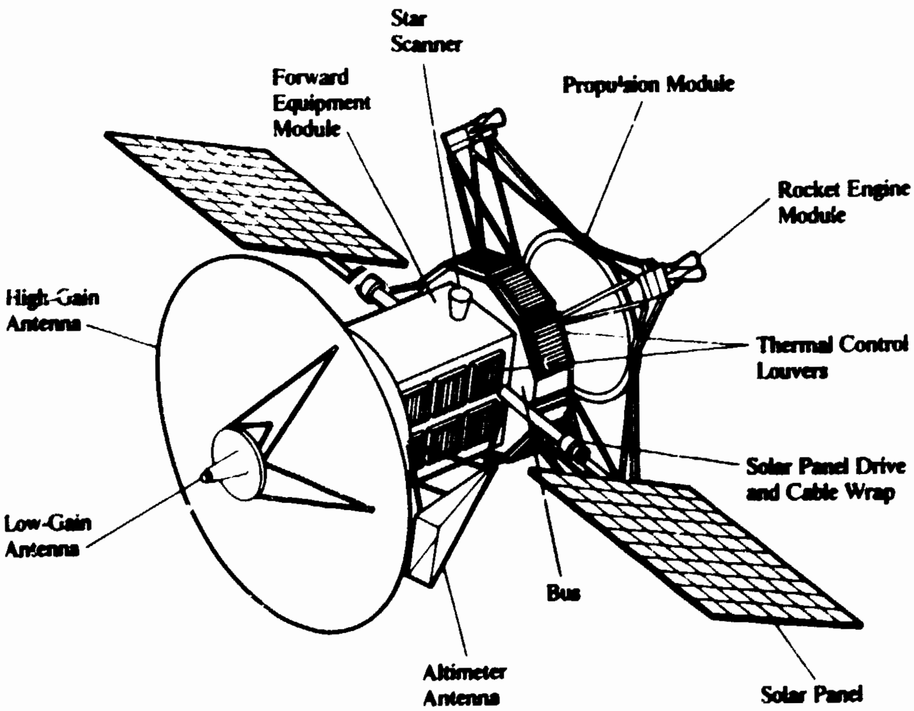
SPACECRAFT CONFIGURATION

The spacecraft consists of a rectangular forward equipment module attached to a bus (a part of the spacecraft that houses various avionics and scientific instruments), a high-gain antenna (used both as the SAR antenna and as the high-rate telecommunications antenna, an altimeter antenna), two solar power arrays, and a propulsion module. The bus contains the command and data system, altitude control propellant, tape recorders, and other electronic components, and the forward equipment module houses the electronic components of the SAR and other electronic equipment. The spacecraft shares several components with the Voyager spacecraft, including the bus and the high-gain antenna. The use of the Voyager antenna lowers SAR resolution. Also, because the spacecraft will be exposed to high-intensity solar radiation, it requires thermal protection for its solar power arrays.

The spacecraft operational configuration and the location of its major components are shown in figure I.1.

Figure I.1: Spacecraft Configuration





COST

At the start of the project in fiscal year 1984, NASA estimated the total cost for development and mission operations & data analysis (MO&DA) at $294.6 million, assuming that the spacecraft would be launched by the Shuttle/Centaur upper stage in April 1988. As a result of a decision to enlarge the scope of SAR investigations and to improve the SAR resolution, problems with SAR development, the Challenger accident, and the Centaur cancellation, the mission cost was estimated in October 1987 at $513.5 million, an increase of about $219 million. The breakdown of the cost increase between fiscal year 1984 and the October 1987 estimates is shown in table I.1.

Table I.1: Breakdown of Estimated Development Cost Increase From Fiscal Year 1984 to October 1987

Activity	Increased estimated costs (millions)
Enlarged scope for SAR	$ 2.7
Launch delay	65.0
Change from Centaur to IUS	13.0
Longer mission operations	12.0
Replacement of Galileo spares	24.0
SAR development problems	
Correction of design problems	24.0
JPL development of SAR digital units	7.0
Increased cost of sensor	3.0
Additional software development	4.0
	38.0
Miscellaneous enhancements/modifications	
Spacecraft	8.0
Memory chip hardening and replacement	3.0
High data rate processor	3.5
Additional scientist	1.5
	16.0
Added reliability for mission operations systems	6.0
Increased mission operations staffing	15.0
JPL contract monitoring	3.0
Increased reserves	25.0
Total	$218.9

Figures do not add to total due to rounding

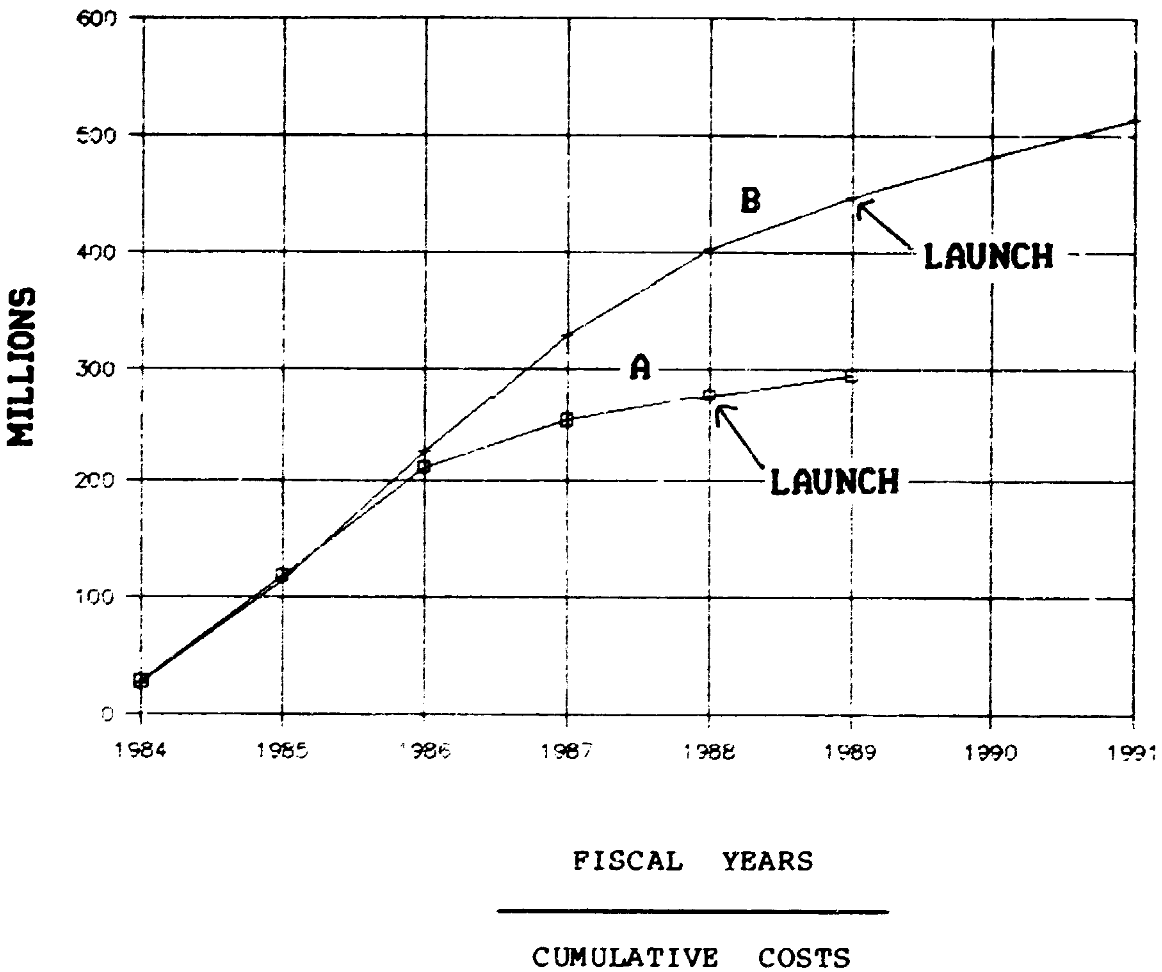
The cost increases and cumulative totals by fiscal year are shown in figure I.2 and table I.2.

Table I.2: Cumulative Costs by Fiscal Year for Development and MO&DA Under Fiscal Year 1984 and October 1987 Estimates

	1984 Estimate			October 1987 Estimate		
FY	Development	MO&DA	Total	Development	MO&DA	Total
	(000 omitted)					
1984	$ 28,431	-	$ 28,431	$ 26,894[a]	-	$ 26,894[a]
1985	119,260	-	119,260	114,720[a]	-	114,720[a]
1986	212,527	-	212,527	225,654[a]	-	225,654[a]
1987	253,833	-	253,833	329,297[a]	-	329,297[a]
1988	267,900	$ 9,000	276,900	402,426	-	402,426
1989	-	26,700	294,600	432,297	$15,293	447,590
1990	-	-	-	-	48,936	481,233
1991	-	-	-	-	81,249	513,546

[a]These are actual cumulative costs.

Figure I.2: Development and MO&DA Costs



CURVE A - INITIAL FISCAL YEAR 1984 ESTIMATE

CURVE B - OCTOBER 1987 ESTIMATE

The annual growth in the project cost estimate is shown in table I.3. Project cost estimates are updated at least twice a year by NASA and represent an estimate of total project cost through completion.

Table I.3: Annual Project Cost Estimate Growth

Fiscal year	Estimated project costs	Annual cost increase
	---(000 omitted)--	
1984	$294,600	-
1985	297,321	$ 2,721
1986	455,482	158,161
1987	513,546	58,064
Total		$218,946

SCHEDULE

At the start of the project in fiscal year 1984, this mission was scheduled for launch in April 1988, and the end of the mission was set for April 1989. However, the launch date has been changed twice. First, after the *Challenger* accident, the launch date was moved to October 1989. Second, the launch date was pushed up to April 1989 so the Galileo spacecraft could use the October 1989 launch date. The current April 1989 launch date requires a trajectory of one and one-half orbits around the sun (called a Type IV trajectory), which delays the arrival at Venus to August 1990, just over 2 years later than the originally planned July 1988 arrival date, which would have used a trajectory of less than one-half of an orbit around the sun (called a Type I trajectory). The launch delay and the cruise time increase will delay the end of the mission by 2 years to 1991. Some of the key milestones in the schedule, as estimated initially in fiscal year 1984 and then in October 1987, are shown in table I.4.

Table I.4: Schedule for the Magellan Mission

Event	Estimate: Initial	Estimate: Oct. 1987	Increase in years
Project start	1984	1984	-
Launch	1988	1989	1
End of mission	1989	1991	2
Project duration (years)	5	7	2

PERFORMANCE

According to project official, the Magellan mission objective to map at least 70 percent of Venus' surface is expected to be achieved, although the April 1989 launch date and the selected Type IV trajectory will place the spacecraft into Venus orbit shortly before solar conjunction. This will interrupt spacecraft communication with earth for about 2 weeks and contribute to a gap in the mapping coverage. According to project officials, if additional funding is available for extending the mission, these gaps could be covered and the spacecraft could achieve total mapping coverage.

MAGELLAN MISSION CHRONOLOGY

1966-77 NASA conducts feasibility studies.

1978 The Space Science Board recommends global mapping of the topography and morphology of Venus.

NASA initiates VOIR studies.

1979 National Research Council recommends a joint US/USSR mission to Venus with an emphasis on global mapping and atmospheric studies.

FY 1979 NASA releases an Announcement of Opportunity for the VOIR mission.

VOIR experiments are selected.

$3.3 million is spent on advanced studies.

FY 1980 $5.4 million is spent on advanced studies.

NASA initiates additional VOIR studies in which alternative designs are considered.

FY 1981 Full-scale development planning for the VOIR mission takes place.

$3.7 million is spent on advanced studies.

FY 1982 NASA requests $40 million to start designing the spacecraft and the SAR for VOIR.

The launch date is tentatively planned for mid-1986. Total project cost are estimated at $545 to $635 million.

VOIR is not initiated due to NASA budget problems.

$2.3 million is spent on advanced studies.

The Solar System Exploration Committee urges a less expensive mission than VOIR that is still capable of achieving basic science objectives, and it recommends the VRM mission as a new project start for FY 1984.

FY 1983 $4.5 million is spent on advanced studies.

NASA cancels the planetary IUS because of performance and budget difficulties and decides to use the Centaur upper stage instead.

FY 1984 VRM is announced as a new project start for FY 1984.

The spacecraft contract is awarded to Martin Marietta Corporation; the SAR contract is awarded to Hughes Aircraft Company.

The launch is scheduled for April 1988 using the Shuttle/Centaur upper stage on a direct ballistic trajectory.

NASA plans to use residual hardware from the Galileo mission (after its launch) for the Magellan spacecraft.

FY 1985 The project confirmation review, a comprehensive cost and status review, is held.

FY 1986 VRM is renamed Magellan.

The Challenger accident occurs.

The residual hardware from the Galileo mission will no longer be available.

The launch date is scheduled for October 1989.

The Centaur upper stage is replaced with an IUS.

FY 1987 The launch date is changed from October 1989 to April 1989.

Final mission design reviews are held.

An early radar test is conducted.

FY 1988 The spacecraft is being assembled, and testing is initiated.

SAR testing is completed.

GLOSSARY

Advanced studies	Studies on the feasibility of the technology, the instruments, and the mission conducted before the official start of a NASA project.
Altimetry	The science or practice of measuring altitudes with an altimeter.
Bus	A spacecraft carrier vehicle for various payloads; it is also a part of a spacecraft housing various avionics and scientific instruments.
Centaur	An expendable, high-performance hydrogen-oxygen cryogenic upper stage used by NASA to launch interplanetary and earth orbital payloads. It was built by the General Dynamics Convair Division.
Density distribution	An experiment designed to measure the density distribution within the crustal mass by observing orbital perturbations of the Magellan spacecraft. Similar investigations of the moon and Mars revealed large concentrations of high-density crustal formations thought to be related to massive meteoric deposits or to formations created by tectonic or volcanic processes.
Direct ballistic trajectory	A path of an unpowered spacecraft governed by gravity and previously acquired velocity.
Gravitational field	That region of space in which appreciable gravitational force exists.
Hardware	A general term for all mechanical and electrical component parts of a computer or data processing system; it is also applied to spacecraft components.
High-gain antenna	A highly sensitive antenna capable of receiving and transmitting radio signals at great distances.

Inertial Upper Stage (IUS)	A rocket booster and associated guidance system that is used to move heavy payloads from a low Earth orbit into higher operational orbits or lighter payloads into deep space trajectories. The solid-fuel IUS was developed jointly by the U.S. Air Force and NASA, and the Boeing Aerospace Company was the prime contractor. The IUS family included two versions of a three-stage Planetary IUS (canceled by NASA in 1982), and a two-stage U.S. Air Force version that will be used to launch the Galileo, Ulysses, and Magellan missions.
Interior dynamics	Geological activity occurring in the interior of a planet at a depth of 100 to 200 kilometers.
Jupiter	The fifth planet from the sun, which is the largest planet in the solar system (318 times the mass of Earth). It has 16 known satellites, with the four largest known as the Galilean moons (Io, Europa, Ganymede, and Callisto).
Launch energy	Twice the energy per unit of mass imparted to a spacecraft measured in relation to Earth's hyperbolic escape trajectory. A hyperbolic escape trajectory resembles a hyperbola, a curve formed by the intersection of a double right circular cone with a plane that cuts both halves of the cone. A spacecraft on a deep space mission is typically launched by the Shuttle into a circular orbit and will require an additional propulsion burn to acquire sufficient velocity to leave the circular orbit and enter a hyperbolic escape trajectory toward the target planet.
Mars	The fourth planet from the sun, which has two known satellites, Phobos and Deimos.
Mission Operations and Data Analysis (MO&DA)	A NASA term that denotes an operational phase of a mission, generally beginning with launch.

Morphology	The external structure, form, and arrangement of rocks in relation to the development of landforms.
New project start	A NASA term that indicates the start of a new project at the beginning of a fiscal year.
Orbiter	A spacecraft or mission involving insertion of a vehicle into orbit around a celestial body; it is also the orbital flight vehicle of the Shuttle system.
Payload	The useful or net weight that is placed into orbit in a space mission.
Residual hardware	Spare hardware that is left after the launch of a spacecraft.
Shuttle	A U.S. Space Transportation System vehicle that place payloads into orbit. It consists of a reusable piloted orbiter with three main engines, two reusable solid rocket boosters, and an expendable liquid propellant tank.
Solar conjunction	The situation in which the sun is in position between two planets. For the Magellan mission, solar conjunction will occur when the sun is between the spacecraft and earth. During this period, the spacecraft-earth communications will be interrupted for about a 2-week period.
Solar power array	A large assembly of photovoltaic (solar) cells.
Synthetic Aperture Radar (SAR)	A radar system utilizing an electromagnetic beam and the motion of a spacecraft to simulate a large antenna size (synthetic aperture) to obtain high-resolution images.
Tectonic	Rock structures that are directly attributable to earth movements involved in folding and faulting.
Topography	The delineation of the natural and artificial features of an area.

Trajectory	The path traced by a rocket or spacecraft moving as a result of an externally applied force, considered in three dimensions. Interplanetary trajectories are commonly classified into several groups. (See direct ballistic, Type I, and Type IV trajectories.)
Type I trajectory	An interplanetary trajectory in which the spacecraft will complete less than one-half of one orbit around the sun (where the angle formed by the injection-point-to-sun line and the arrival-point-to sun line is from 0 to 180 degrees).
Type IV trajectory	An interplanetary trajectory in which the spacecraft will complete at least one and one-half orbits around the sun (where the angle formed by the injection-point-to-sun line and the arrival-point-to sun line is from 540 to 720 degrees).
Upper stage	A vehicle that is used to propel payloads into higher-than-earth orbit, interplanetary trajectories, or other high-energy orbital maneuvers.
Venus	The second planet from the sun.
Venus Orbiting Imaging Radar (VOIR)	The initial mission planned by NASA to investigate Venus, which was scaled down and renamed the Venus Radar Mapper and later renamed the Magellan mission.
Venus Radar Mapper (VRM)	The scaled-down Venus Orbiting Imaging Radar mission, which was later renamed Magellan.
Voyager	Missions to Jupiter and Saturn in which the Voyager I and II spacecrafts were launched in 1973 and 1975, respectively. Both missions returned a wealth of information on the planets and their satellites.

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*U.S. G.P.O. 1988-201-749:80130

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