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United States General Accounting Office

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 Galileo Mission to Jupiter

GAO/NSIAD-88-138FS

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 Galileo mission to Jupiter. 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 objectives of the Galileo mission are to investigate the chemical composition and physical state of Jupiter's atmosphere and satellites and to study the structure and

[1]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 Magellan Mission to Venus (GAO/NSIAD-88-130FS, May 27, 1988); Space Exploration: Cost, Schedule, and Performance of NASA's Mars Observer Mission (GAO/NSIAD-88-137FS, May 27, 1988).

physical dynamics of Jupiter's magnetosphere, that is, its magnetic field. At the start of the project in fiscal year 1978, NASA estimated its total cost at $410.1 million. However, in October 1987, the cost estimate was $1,362.5 million, an increase of $952.4 million. The increase in the cost estimate was primarily due to Shuttle launch delays, changes to the upper stage, which provides the propulsion for interplanetary trajectory, and the Challenger accident.

The launch date, originally scheduled for January 1982, has been delayed by over 7 years; the current launch date is set for October 1989. The end of the mission, initially set for 1987, will be delayed by an estimated 10 years, until 1997. Under previous launch schedules, the shortest cruise time--the amount of time it would take a spacecraft to reach its destination--to Jupiter was 26 months; now, under the current launch schedule, the cruise time to Jupiter will be 72 months, an increase of almost 4 years.

According to project staff, this mission is expected to exceed its initial objectives. The launch delays and the extended cruise time have allowed NASA to expand the scope of the scientific investigations and to add or enhance scientific instruments.

As requested, we did not obtain official agency comments. However, we discussed this 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
Senior Associate Director

Contents

ABBREVIATIONS

Delta VEGA	Delta Velocity-Earth-Gravity-Assist trajectory
IUS	Inertial Upper Stage
JPL	Jet Propulsion Laboratory
MO&DA	Mission operations and data analysis
NASA	National Aeronautics and Space Administration
RTG	Radioisotope Thermoelectric Generator
VEEGA	Venus-Earth-Earth-Gravity-Assist trajectory

GALILEO MISSION TO JUPITER

The Galileo mission to Jupiter is a scientific descendant of the successful Voyager fly-by missions to Jupiter and its moons. The Galileo project started in fiscal year 1978, and its launch was initially scheduled for 1982. Its launch is now scheduled for 1989.

The primary objectives of this mission are to investigate the chemical composition and physical state of Jupiter's atmosphere and satellites and to study the structure and dynamics of the Jupiter's magnetosphere (i.e., its magnetic field). According to the National Aeronautics and Space Administration (NASA), the unique combination of capabilities provided by the Galileo orbiter and its atmosphere probe is intended to extend our knowledge greatly about the evolution of planetary systems. The orbiter will provide 22 months of orbital operations that will map Jupiter's surface and its magnetosphere and will investigate its four closest satellites.

This mission is the first planned outer planet[2] mission to

-- perform a detailed observation of Jupiter's system;

-- send an orbiter around an outer planet and a probe into the atmosphere of an outer planet; and

-- use a dual-spin spacecraft (a spacecraft with one spinning section and one nonspinning section) and a complex Venus-Earth-Earth-Gravity-Assist (VEEGA) trajectory (which uses one fly-by[3] of Venus and two fly-bys of earth before heading for Jupiter), to compensate for the lack of a high-energy upper stage, which is used to propel a spacecraft into orbit.

The VEEGA trajectory extends the spacecraft cruise time from 26 to 72 months, thus increasing mission risk and operations cost. This trajectory will expose the orbiter to high temperatures during the Venus fly-by and thus will increase the possibility of thermal damage. The extended cruise time increases the spacecraft's exposure to radiation, micrometeorite impacts, and hardware failure due to aging.

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[2]The outer planets are Jupiter, Saturn, Uranus, Neptune and Pluto.

[3]A fly-by is an interplanetary mission in which a spacecraft passes close to a planet but does not impact it or go into orbit around it.

The spacecraft is scheduled to carry 19 instruments/investigations, 12 by the orbiter and 7 by the probe. These instruments/investigations are listed below with the country supplying the equipment. A brief explanation of each of these instruments/investigations can be found in the glossary.

Orbiter Instruments/Investigations	Supplied by
Magnetometer	United States
Plasma detector	United States
Energetic particle detector	United States/ West Germany
Plasma wave spectrometer	United States
Dust detection instrument	West Germany
Celestial mechanics	United States
Radio propagation	United States
Solid state imaging	United States
Ultraviolet spectrometer	United States
Near infrared mapping spectrometer	United States
Photopolarimeter radiometer	United States
Extreme ultraviolet spectrometer	United States

Probe Instruments/Investigations	
Atmosphere structure instrument	United States
Neutral mass spectrometer	United States
Helium abundance interferometer	West Germany
Nephelometer	United States
Net flux radiometer	United States
Lightning and radio emission instrument	West Germany
Energetic particle detector	West Germany

This project has 15 principal investigators and 13 scientists for interdisciplinary investigations.

According to the Jet Propulsion Laboratory (JPL), NASA's primary contractor for the mission, the launch delays and extended mission cruise time allowed them the opportunity to plan for expanding the scope of Galileo's scientific investigations and to add or enhance scientific instruments. Expanded mission opportunities include an asteroid encounter, an investigation of clouds and lightning on Venus, a study of the recently reported "1 astronomical unit hydrogen shell" surrounding the sun,[4] observations of the earth's extended geotail and antitail, and

[4]The hypothetical hydrogen shell located at the distance of 1 astronomical unit (150 million kilometers or 93 million miles from the sun) is thought to be created by the evaporation of small, unseen comets.

observations of the lunar farside, Mare Orientale, and lunar polar regions.

The delays in this project required JPL project staff to develop several trajectory options. They are

-- an initial direct ballistic trajectory using NASA's three-stage Inertial Upper Stage (IUS),

-- a Mars Gravity Assist trajectory for the combined 1982 launch (the spacecraft and the probe launched together),

-- a Mars Gravity Assist trajectory for the 1984 separate launch of the orbiter and a direct ballistic trajectory for the probe,

-- a Delta velocity-earth-gravity-assist (Delta VEGA) trajectory for the combined August 1985 launch,

-- a direct ballistic trajectory for the combined 1986 launch, and

-- a VEEGA trajectory for the combined 1989 launch.

These trajectories are described in the glossary.

At the beginning of the project in 1978, NASA was planning to launch the spacecraft Galileo in January 1982 on a direct ballistic trajectory using NASA's three-stage IUS. However, Shuttle and IUS launch performance limitations and growth in the weight of the spacecrafts required NASA to incorporate a Mars fly-by to obtain gravity assist energy--which gives the spacecraft sufficient added velocity by aiming it toward a planet to use the planet's free gravitational pull--to reach Jupiter.

Due to Shuttle launch delays, NASA had to postpone the 1982 launch date to 1984. This resulted in a less favorable launch opportunity; therefore, NASA split the mission into two separate launches. The orbiter, augmented by an auxiliary upper stage, was to be launched on a Mars gravity assist trajectory, and the probe was to be launched on a direct ballistic trajectory. The cruise times for the orbiter and probe were estimated at 28 and 40 months, respectively.

In 1981, as a result of cost increases in the three-stage IUS program, NASA replaced the IUS with the more powerful Centaur upper stage. With the Centaur, NASA could once again plan to launch the orbiter and the probe as a single payload on a direct ballistic trajectory.

In early 1982, NASA canceled the Centaur upper stage for the Shuttle because of fiscal year 1981 budgetary problems and replaced it with a two-stage IUS with an injection module. Since this was a less powerful upper stage than the three-stage IUS and the Centaur, a new Delta VEGA trajectory was proposed with a cruise time of 52 months.

When the Congress directed NASA to use the Centaur upper stage in late 1982, a direct ballistic trajectory with a cruise time of only 28 months was again possible. However, after the Challenger accident in January 1986, NASA canceled the Centaur for the Shuttle because of safety concerns about carrying liquid fuel in the shuttle cargo bay. NASA has since selected a solid-fuel two-stage IUS, a less powerful but safer option, that will be launched on a VEEGA trajectory with a cruise time of 72 months.

OBJECTIVES, SCOPE, AND METHODOLOGY

Our objectives were to describe this mission and to obtain information on cost, schedule, and performance, including a year-by-year analysis of project cost increases. 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. To prepare a year-to-year analysis of cost increases for this mission, we identified the annual cost increases and discussed their major causes with project managers.

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 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

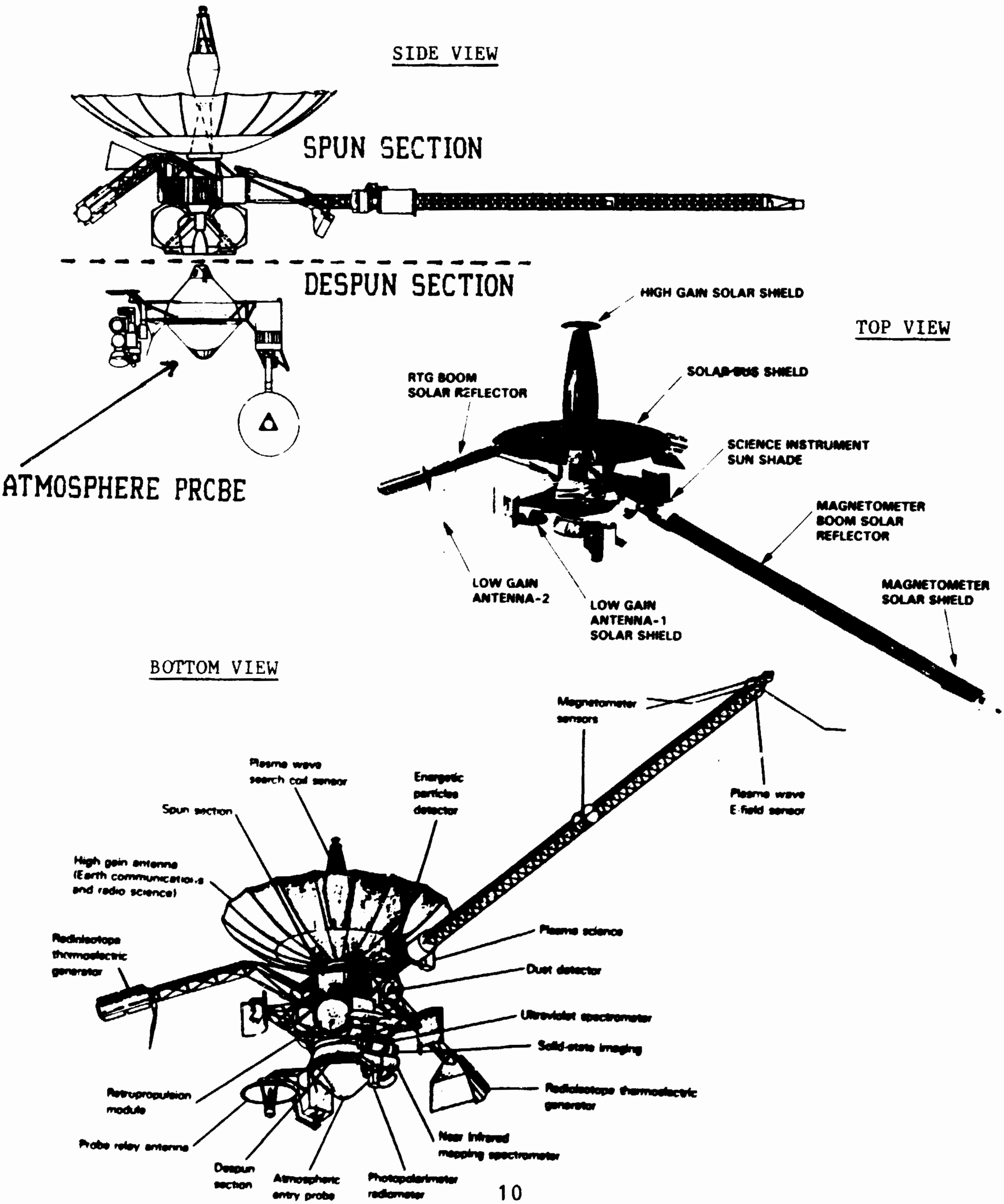
According to JPL officials, the Galileo orbiter is the most complex spacecraft that JPL has ever developed. It is a "dual-spin" spacecraft consisting of a spinning (spun) and nonspinning (despun) sections. The spun section of the orbiter is designed to allow instruments to measure electromagnetic fields and particles in space, and the despun section provides a stable platform for cameras and other remote sensing instruments for making observations of points on the planet's surface. The two sections are connected by a spin bearing assembly, which mechanically couples the two parts of the orbiter and transfers electrical signals. The despun section of the orbiter also carries the probe, which is designed to sample Jupiter's atmosphere. The spacecraft operational configuration and its major components are shown in figure I.1.

The orbiter will release an approximately 750-pound acorn-shaped probe that will enter Jupiter's atmosphere at nearly 100,000 miles per hour, the fastest atmospheric entry ever attempted. The probe is designed to have its descent checked by a parachute, and to slow to about 2,000 miles per hour while losing about one-half of its mass through ablation of its heat shield. During its descent, the probe will sample Jupiter's atmosphere and relay data to the orbiter passing overhead. The increasing temperature and pressure are expected to destroy the probe after about 1 hour when it will be 130 kilometers below Jupiter's cloud cover.

The orbiter is powered by two Radioisotope Thermoelectric Generators (RTGs)--an electrical power generator consisting of a heat source and a system for the conversion of heat to electricity--developed by the U.S. Department of Energy; the probe is powered by a battery. The spacecraft retro-propulsion system, which is used for orienting the spacecraft attitude and for trajectory correction maneuvering, was developed by West Germany.

Figure I.1 shows recent modifications to the orbiter, including solar shields and reflectors for heat-sensitive components (see the top view). The spacecraft was originally designed to operate between 1 and 5 astronomical units from the sun. The new VEEGA trajectory will bring the spacecraft as close as 0.59 astronomical units from the sun, which will expose it to solar intensity nearly three times that of the earth. Thermal protection for the heat-sensitive hardware includes shielding the spacecraft bus, instruments, and magnetometer boom with high-temperature-resistant thermal blankets.

Figure I.1: Spacecraft Configuration



COST

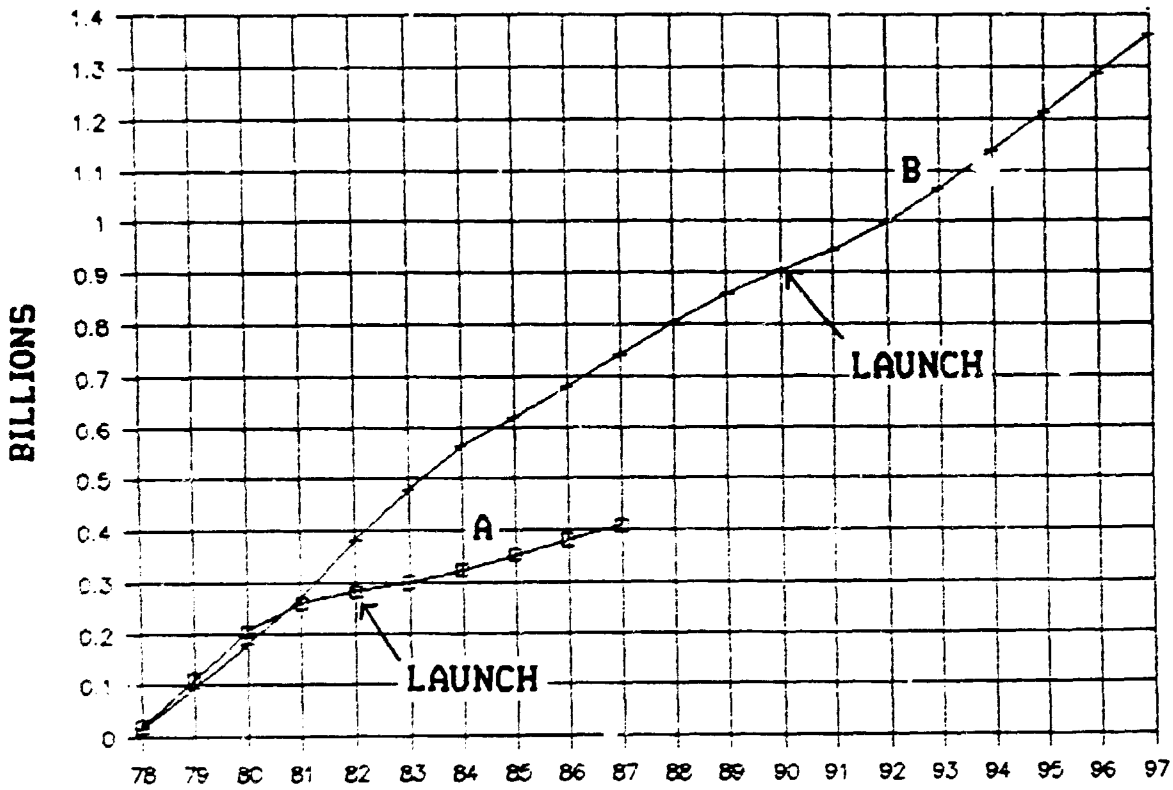
At the start of this project in 1978, NASA had estimated the total cost of the mission to be $410.1 million--$271.3 million for development and $138.8 million for mission operations and data analysis (MO&DA). By October 1987, the cost estimate had increased by $952.4 million to $1,362.5 million--$878.3 million for development and $484.2 million for MO&DA. This increase is primarily due to Shuttle launch delays, changes in the upper stage, and mission changes resulting from the Challenger accident. The cost increases between fiscal year 1978 and October 1987 estimates are shown in figure I.2 and table I.1.

Table I.1: Cumulative Costs by Fiscal Year for Development and MO&DA Under Fiscal Year 1978 and October 1987 Estimates

	1978 estimate			October 1987 estimate		
FY	Development	MO&DA	Total	Development	MO&DA	Total
	(000 omitted)					
1978	$ 20,300	-	$ 20,300	$ 17,159[a]	-	$ 17,159[a]
1979	112,551	-	112,551	96,756[a]	-	96,756[a]
1980	204,378	-	204,378	181,230[a]	-	181,230[a]
1981	259,981	-	259,981	270,529[a]	-	270,529[a]
1982	271,300	$ 11,296	282,596	380,223[a]	-	380,223[a]
1983	-	28,097	299,397	478,905[a]	-	478,905[a]
1984	-	52,819	324,119	562,463[a]	-	562,463[a]
1985	-	81,479	352,779	619,373[a]	-	619,373[a]
1986	-	110,139	381,439	680,832[a]	-	680,832[a]
1987	-	138,799	410,099	741,326	-	741,326
1988	-	-	-	801,926	-	801,926
1989	-	-	-	859,336	-	859,336
1990	-	-	-	878,302	$ 26,100	904,402
1991	-	-	-	-	62,800	941,102
1992	-	-	-	-	121,300	999,602
1993	-	-	-	-	183,500	1,061,802
1994	-	-	-	-	258,675	1,136,977
1995	-	-	-	-	333,850	1,212,152
1996	-	-	-	-	409,025	1,287,327
1997	-	-	-	-	484,200	1,362,502

[a]These are actual cumulative costs.

Figure I.2: Development and MO&DA Costs



FISCAL YEARS

CUMULATIVE COSTS

CURVE A - INITIAL FISCAL YEAR 1978 ESTIMATE

CURVE B - OCTOBER 1987 ESTIMATE

The annual increase in the project cost estimates are shown in table I.2. The project costs are estimated at least twice each year by NASA and represent an estimate of total project cost through completion.

Table I.2: Annual Project Cost Estimate Growth

Fiscal year	Estimated project costs	Annual cost increase
	----(000 omitted)----	
1978	$ 410,100	$ -
1979	445,970	35,870
1980	623,809	177,839
1981	662,100	38,291
1982	829,650	167,552
1983	833,500	3,848
1984	844,069	10,569
1985	881,828	37,759
1986	882,375	547
1987	1,362,502	480,127
Total		$952,402

Since fiscal year 1978, the total project costs estimate has increased by an average of $106 million annually.

In fiscal year 1979, the estimate increased $35.9 million to $446 million--$20.9 million for development and $15.0 million for MO&DA. According to the project staff, this increase reflects adjustments made to initial estimates based on a more detailed work breakdown structure that identified additional costs.

Between fiscal years 1979 and 1980, NASA decided to split the mission and launch the orbiter and probe as separate Shuttle payloads in 1984. Thus, the fiscal year 1979 estimate of $446 million was increased $177.8 million to $623.8 million, $174.3 million for development and $3.5 million for MO&DA. This increase was primarily due to changes required by the split mission, such as

- -- modification of the orbiter to eliminate the probe,
- -- design of a new spacecraft carrier for the probe,
- -- design and development of an auxiliary upper stage for the orbiter,
- -- integration of an IUS with the probe,
- -- acquisition of additional flight subsystems for the probe,
- -- modification of the orbiter's trajectory, and

-- development of a direct ballistic trajectory for the probe.

The cost increase was partly offset by estimated operational cost savings due to the shorter mission. The cost estimate increase is summarized in table I.3.

Table I.3: Project Cost Increase for Fiscal Years 1979-80

Changes or modifications	Change in estimated cost (millions)
Acquisition of additional spacecraft to carry the probe	$ 56.5
1984 launch and mission changes	105.9
Mars fly-by module and adapter	
Thermal shielding	
Change of RTGs	
Mission analysis	
Trajectory replanning	
Redesign of mechanical devices	
Development of probe redundancy	7.0
Development of software management plan for the Attitude and Articulation Control System	4.9
Total development cost increase	**174.3**
Split mission operations for carrier subsystem	2.5
Inflation	22.0
Savings due to shorter mission	- 21.0
Total MO&DA cost increase	**3.5**
Total	**$177.8**

The project cost increase from fiscal year 1980 to 1981 can be contributed primarily to NASA's decision to replace the three-stage IUS with the more powerful Centaur. The fiscal year 1980 estimate of $623.8 million was increased $38.3 million to $662.1 million, $40.8 million more for development and $2.5 million less for MO&DA. The cost increases were primarily due to modifications required by the change from the three-stage IUS to the Centaur, such as

-- eliminating the completed, but no longer required, Mars fly-by module (auxiliary upper stage) developed for the orbiter,

-- recombining the orbiter and probe into a single spacecraft, and

-- developing a new orbiter/Centaur interface and a new direct ballistic trajectory.

The cost estimate change is summarized in table I.4.

Table I.4: Project Cost Increase for Fiscal Years 1980-81

Changes or modifications	Change in estimated cost (millions)
Centaur 1985 launch modifications:	$88.2
Development of structure and adapter for the Centaur upper stage	
Thermal shielding	
Mission analysis	
Trajectory replanning	
Redesign of mechanical devices	
Launch vehicle integration/modifications	
RTG replacement	9.1
Inflation	10.0
Cancellation of the separate probe spacecraft	-56.5
Savings due to shorter mission	-10.0
Total development cost increase	40.8
Recombined mission (single launch)	- 2.5
Total MO&DA cost decrease	- 2.5
Total	$38.3

The estimated project cost increase from fiscal year 1981 to 1982 was caused by NASA's cancellation of Centaur development due to budget problems and its decision to launch the spacecraft on a Delta VEGA trajectory using a two-stage IUS and an injection module. The fiscal year 1981 estimate increased $167.6 million to $829.7 million, $45.6 million for development and $122 million for MO&DA. This increase was primarily due to the longer mission, as shown in table I.5.

Table I.5: Project Cost Increase for Fiscal Years 1981-82

Changes or modifications	Change in estimated cost (millions)
Modifications for 1985 launch (replacement of the Centaur upper stage with IUS) using a Delta VEGA trajectory	$ 11.6
Development of IUS structure and adapter	
Thermal shielding	
Mission analysis	
Trajectory replanning	
Redesign of mechanical devices	
Launch vehicle integration/modifications	
Modification of IUS and development of an Injection Module for the orbiter	34.0
Total development cost increase	**45.6**
Increase in mission operations cost due to a longer mission	122.0
Total MO&DA cost increase	**122.0**
Total	**$167.6**

In late fiscal year 1982, the Congress directed NASA to use the Centaur upper stage on this mission. Replacing the two-stage IUS with Centaur caused some hardware and mission redesign, including a new orbiter/Centaur interface and a restart of Centaur-specific modifications terminated earlier. As a result, estimated project costs increased slightly in fiscal year 1983 by $3.8 million to $833.5 million, $98.6 million more for development and $94.8 million less for MO&DA (see table 1.6).

Table I.6: Project Cost Increase for Fiscal Years 1982-83

Changes or modifications	Change in estimated cost (millions)
Replacement of IUS with Centaur	$131.4
Development of Centaur and adapter	
Mission analysis	
Trajectory replanning	
Redesign of mechanical devices	
Analysis of new loads	
Launch vehicle integration/modifications	
Cancellation of two-stage IUS and injection module	- 32.8
Total development cost increase	98.6
Increase of mission operations cost after design review	16.0
Inflation	11.2
Decrease in mission operations cost due to a shorter mission	-122.0
Total MO&DA cost decrease	- 94.8
Total	$ 3.8

In fiscal year 1984, the project cost estimate increased by $10.6 million to $844.1 million, $14.3 million more for development and $3.7 million less for MO&DA. This increase was primarily due to the modifications of the spacecraft's electronic subsystems, as shown in table I.7.

Table I.7: Project Cost Increase for Fiscal Years 1983-84

Changes or modifications	Change in estimated cost (millions)
Hardening electronics against radiation	$14.5
Miscellaneous development adjustments	- 0.2
Total development cost increase	**14.3**
Miscellaneous MO&DA adjustments	- 3.7
Total MO&DA cost decrease	- 3.7
Total	**$10.6**

The project cost estimate increased in fiscal year 1985 by $37.7 million to $881.8 million, $3.7 million for development and $34 million for MO&DA. This increase was primarily due to rephasing a communications uplink and correcting problems with computer memory chips and software. The required modifications and their estimated costs are shown in table I.8.

Table I.8: Project Cost Increase for Fiscal Years 1984-85

Changes or modifications	Change in estimated cost (millions)
Payback to NASA	$ 6.9
Headquarters administrative costs	3.7
Deferred development	- 6.9
Total development cost increase	**3.7**
Memory chip and software rework	$10.5
Rephasing of communications uplink	22.5
RTG development shortfall	1.0
Total MO&DA cost increase	**34.0**
Total	**$37.7**

The project cost estimate increased slightly in fiscal year 1986 by $0.6 million to $882.4 million, $9.3 million more for development and $8.7 million less for MO&DA. The increase in the development estimate was to be used to correct design problems discovered during testing. The MO&DA estimate decrease was a result of various other adjustments.

The project cost estimate increased in fiscal year 1987 by $480.1 million to $1.36 billion, $199.6 million for development and $280.5 million for MO&DA. This increase was due to the Challenger accident in January 1986, which resulted in a broad safety review of the Shuttle program, including the evaluation of risks associated with the Centaur. Unlike the solid-fuel IUS under consideration in the earlier stages of this project, Centaur engines are powered by liquid fuels, including oxygen, hydrogen, and hydrazine. Because of concerns about the safety of carrying liquid propellants in the Shuttle cargo bay, NASA canceled the Centaur and returned to the solid propellant two-stage IUS. The Challenger accident and the decision to replace the Centaur with an IUS required many changes in both hardware and mission design, which include

-- developing a VEEGA trajectory because of the low-energy performance of the new IUS,

-- replacing of aging components,

-- reconfiguring the electrical system to compensate for the reduction of power produced by an aging RTG,

-- designing and developing thermal protection for the orbiter and probe, and

-- increasing the length and cost of mission operations time.

The cost estimate increase is summarized in table I.9.

Table I.9: Project Cost Increase for Fiscal Years 1986-87

Changes or modifications	Change in estimated cost (millions)
Two-stage IUS launch in 1989 on VEEGA trajectory. Modifications included	$181.2
Probe and orbiter science	
Spacecraft system engineering	
Electronic subsystems	
Replacement of orbiter spare given to Magellan	
Probe engineering and operations	
System integration	
Mechanical subsystems	
Integration test program	
Navigation	
Flight and ground software	
Mission operations design	
System test support	
Orbiter flight operations	
Project management	
RTG storage	1.6
Explosion tests	3.0
Memory rebuild	4.4
RTG shielding	2.8
Final safety analysis report	4.4
Shelf life and aging studies	2.2
Total development cost increase	199.6
Longer mission operations	280.5
Total MO&DA cost increase	280.5
Total	$480.1

SCHEDULE

The launch date, originally scheduled for January 1982, has been delayed by over 7 years; the current launch date is set for October 1989. The end of the mission, initially set for 1987, will be delayed by 10 years, until 1997. The shortest cruise time to Jupiter (using the Centaur upper stage) was 26 months; the current cruise time (using two-stage IUS) is 72 months, an increase of almost 4 years.

Most of the delays in the pre-*Challenger* period (1978 to 1985) were due to Shuttle launch delays and four changes in the upper stage vehicle. Project delays after the *Challenger* accident have been due to the temporary suspension of the Shuttle program and the lack of an alternative launch vehicle. The overall schedule delay and upper stage changes are summarized in table I.10.

Table I.10: Schedule and Upper Stage Changes

Event	Estimate Initial	Estimate Oct. 1987	Increase in years
Project start	1978	1978	-
Launch	1982	1989	7
End of mission	1987	1997	10
Project duration (years)	9	19	10

Launch type	Upper stage vehicle	Trajectory	Year constructed
Combined	Planetary IUS	Direct	1978
Split	Planetary IUS	Direct	1980
Combined	Centaur	Direct	1981
Combined	IUS with injection module	Delta VEGA	1982
Combined	Centaur	Direct	1982
Combined	IUS	VEEGA	1986

PERFORMANCE

According to project staff, this mission is expected to achieve all its original objectives. In addition, because of the launch delays and the extended mission cruise time, NASA has been able to expand the scope of its scientific investigations and to add or enhance scientific instruments. Specifically, (1) a new Time-of-Flight sensor will be installed for the Energy Particle Detector provided by West Germany to improve the ion composition measurements and (2) an extreme ultraviolet sensor will be added to operate as a spin-scan imager to enhance magnetospheric studies. (NASA will use a spare Voyager instrument to gather the information on ultraviolet emissions.)

Because of project delays, the aging of the spacecraft's hardware is a serious concern of JPL. Some of the components are reaching the end of their lifetime and have to be replaced. The aging effects include loss of adhesion in conductive tapes, degradation of flexibility in electrical cables, corrosion of metal parts, and the fracturing of O-rings. The scope of the metal parts, and the fracturing of O-rings. The scope of the replacement effort is extensive. For example, the orbiter's electrical systems contain nearly 25,000 feet of electrical cables and over 700 connectors. JPL has addressed the hardware aging problems by conducting shelf-life and aging studies that include

-- general review of subsystems, parts, and materials;

-- identification of items of concern;

-- investigations of light-emitting diodes (a device with low resistance to electric current in one direction and high resistance in reverse direction), critical components of the spin bearing assembly; and

-- studies of the impact of electromigration on the orbiter's electronics.

The spacecraft is powered by two 285-watt RTGs fueled by plutonium-238. Each 122-pound RTG carries about 24 pounds of plutonium oxide in the form of cylindrical pellets. Because the half-life of plutonium-238 is approximately 88 years, a significant portion of the fuel has decayed. Since the RTGs will produce less power, JPL is implementing numerous power-reduction modifications to allow the spacecraft to function at reduced power levels without detrimental effects on the science objectives.

GALILEO PROJECT CHRONOLOGY

FY 1978 NASA announces the start of the Galileo project. The mission is a follow-up on the first fly-by of Jupiter by Pioneer 10 and 11 and the encounter by Voyager in 1979.

The launch is scheduled for January 1982 using the Shuttle and NASA's three-stage IUS (known also as the Planetary IUS) on a direct ballistic trajectory.

NASA advises JPL that the Shuttle's payload limit and the growth in weight of the orbiter and IUS will require a new launch trajectory.

JPL develops Mars Gravity Assist trajectory to compensate for the payload weight limitations.

FY 1979 NASA advises JPL that the launch will be delayed because of the delays in the Shuttle's launch schedule. NASA does not identify a new launch date at this time.

JPL evaluates alternative launch options.

FY 1980 In January 1980, NASA decides to split the mission and to launch the orbiter and probe as separate Shuttle payloads.

The launch is scheduled for early 1984.

NASA discovers that the orbiter must be equipped with an auxiliary upper stage because the launch is scheduled when the earth and Jupiter are not in an optimal position.

The orbiter, augmented by an auxiliary upper stage, is scheduled to be launched on a Mars Gravity Assist trajectory using NASA's three-stage IUS.

The probe is scheduled to be launched on a direct ballistic trajectory using NASA's three-stage IUS.

The launch date for the orbiter is changed to February 1984, and the launch date for the probe is scheduled 1 month later in March 1984.

JPL proceeds with mission redesign and developing a spacecraft carrier for the probe and an auxiliary upper stage for the orbiter.

FY 1981 Cost increases in the three-stage IUS program result in NASA's decision to cancel its three-stage IUS and to plan the launch using the Centaur upper stage. The change from the low-energy, solid-fuel IUS to the high-energy, liquid-fuel Centaur allows JPL to recombine the orbiter and probe and to launch both as a single payload, using a direct ballistic trajectory.

The launch is postponed from February and March 1984 to April 1985 to allow NASA to develop the Centaur.

JPL continues to design the orbiter and probe and to develop an orbiter/Centaur interface.

FY 1982 NASA decides to cancel the Centaur project due to budget problems. As a result, NASA advises JPL that this mission is to be launched using the U.S. Air Force two-stage IUS.

The lower performance of the two-stage IUS requires the development of an injection module (auxiliary upper stage) and a new trajectory.

JPL adopts Delta VEGA trajectory.

The launch is scheduled for August 1985.

JPL proceeds with mission redesign and developing an auxiliary upper stage for the orbiter.

The Congress directs NASA to restart the Centaur project and to use the Centaur as the upper stage.

A new launch date is set for May 1986 to allow NASA to complete the development of the Centaur and JPL to develop Galileo/Centaur interfaces, redesign the mission, and develop a new trajectory.

FY 1983 JPL continues to develop the orbiter and probe and mission design.

JPL modifies the spacecraft's subsystems to decrease the sensitivity of electronic components to cosmic rays.

FY 1984 JPL continues to develop the orbiter and probe and mission design.

JPL fabricates memory components and modifies flight software.

FY 1985 JPL continues to develop the orbiter and probe and mission design.

JPL rework the spin bearing assembly and memory components.

FY 1986 The Challenger accident occurs.

Because of safety concerns with the liquid-fueled Centaur and with the Shuttle mission abort landing weight, NASA replaces the Centaur upper stage with the U.S. Air Force two-stage IUS and lowers the Shuttle payload limit from 65,000 to 51,100 pounds.

Lowering the Shuttle payload limit precludes the use of the injection module developed by JPL for the Delta VEGA launch and requires a new trajectory.

JPL develops the VEEGA trajectory to compensate for the replacement of the high-energy Centaur with a less powerful IUS.

NASA postpones the launch from May 1986 to October 1989.

JPL begins to evaluate the impact of launch delays and cruise time extension on this mission and its hardware.

FY 1987 The spacecraft is returned to JPL for storage, and its science instruments are removed and returned to scientists for modifications and recalibration.

Project staff is conducting aging studies, developing energy saving designs to compensate for the loss of power output from the aging RTGs, and designing major changes in the orbiter hardware to protect the spacecraft from the sun.

GLOSSARY

Ablation	A form of mass heat transfer cooling that involves the burn-off of surface material from a space reentry vehicle or probe.
Antitail	The portion of magnetosphere extending from earth in the direction toward the sun.
Asteroid	Any of a host of small rocky astronomical objects found primarily between the orbits of Mars and Jupiter. There are about 2,000 known asteroids in the solar system.
Astronomical unit	A unit of length used in measuring astronomical distances that is equal to the mean distance of the earth from the sun (approximately 150 million kilometers or 93 million miles).
Attitude	The orientation of a spacecraft as defined by the inclination of its axis to the orbital plane.
Atmosphere structure instrument	An instrument that provides information about temperature, density, pressure, and molecular weight to determine the structure of an atmosphere.
Auxiliary upper stage	A supplemental propulsion system used to inject a spacecraft into an orbit or trajectory; it may be integrated either with the spacecraft or with an Inertial Upper Stage.
Bus	A spacecraft carrier vehicle for various payloads; it is also a part of a spacecraft housing various avionics and scientific instruments.

Celestial mechanics	A study of motion of celestial bodies under the influence of gravitational fields; it is a Galileo mission experiment using the radio system and high-gain antenna to determine the mass and orbit of Jupiter and its satellites.
Centaur	An expendable, high-performance hydrogen-oxygen cryogenic upper stage used by NASA to launch interplanetary and earth orbital payloads.
Delta velocity earth-gravity-assist (Delta VEGA) trajectory	One of the trajectories for the Galileo mission, which requires a large propulsive maneuver in deep space in conjunction with a subsequent earth gravity assist. This trajectory was used by the Voyager mission.
Despun platform	A platform designed to keep scientific instrument pointed in a specific direction.
Direct ballistic trajectory	A trajectory of an unpowered spacecraft governed by gravity and previously acquired velocity.
Dual-spin spacecraft	A spacecraft with one spinning section and one nonspinning section.
Dust detection instrument	An instrument that determines the size, speed, and charge of small particles such as micrometeorites.
Electromagnetic fields	The field of force associated with electric charge in motion that has both electric and magnetic components and contains a definite amount of electrical and magnetic energy.
Electromigration	A type of erosion affecting transistors that use aluminum substrate metallization, which results in a mass movement or migration of metal caused by thermally activated metal ions and conducting electrons.

Energetic particle detector	An instrument that measures energetic electrons and protons, determines their spatial distributions, and measures particles trapped in a magnetic field.
Expendable launch vehicle	A nonreusable rocket such as the Titan IV.
Extreme ultraviolet	Electromagnetic radiation with a wavelength between 10 and 185 nanometers.
Fly-by mission	An interplanetary mission in which the spacecraft passes close to the target planet but does not impact it or go into orbit around it.
Geotail	The portion of the magnetosphere extending from earth in the direction away from the sun for a distance of about 1,000 earth radii.
Gravity assist	A technique used to give a spacecraft sufficient added velocity by aiming it toward a planet to use the planet's gravitational pull.
Half-life	An interval of time required for one-half the atomic nuclei of a radioactive substance to disintegrate (change spontaneously into another element).
Helium abundance interferometer	An instrument that measures the ratio of hydrogen to helium with high accuracy.
Inertial Upper Stage (IUS)	A rocket booster and associated guidance system designed for the Shuttle that is used to move heavy payloads from a low earth orbit into higher operational orbits or to move 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 (1) two versions (spin stabilized and 3-axis stabilized) of a three-stage Planetary IUS (canceled by NASA in 1982) and (2) a two-stage U.S. Air Force version that will be used to launch the Galileo, Ulysses, and Magellan missions.

Injection module	A solid-fuel rocket designed to accelerate a spacecraft to a trajectory injection speed. It is frequently used in tandem with an IUS.
Interdisciplinary investigations	Investigations beyond the principal experiments in which scientists work with the data from several experiments and provide a broad link among many disciplines.
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 vehicle	A rocket used to laurch a missile or space vehicle; it is also called a booster rocket.
Light-emitting diode	A two-terminal device with low resistance to an electric current in one direction and high resistance in the other direction. It produces light as currents passes through it.
Lightning and radio emission instrument	An instrument that measures electromagnetic waves being generated by lightning flashes in an atmosphere; it detects the light and radio transmissions from those flashes.
Liquid propellant	A liquid substance that propels or provides thrust as an explosive charge or a rocket fuel.
Lunar farside	The part of the moon's surface permanently hidden from direct earth observation.
Magnetometer	An instrument used for comparing the intensity and direction of magnetic fields.
Magnetosphere	An asymmetric region (generally spherical) within which the magnetic field of a planet is confined by the solar wind.

Mare Orientale	A circular plane made of basaltic material that fills the interior part of the Orientale basin on the moon.
Mars	The fourth planet from the sun, which has two known satellites, Phobos and Deimos.
Mars gravity assist trajectory	A trajectory used on the Galileo mission that utilizes a Mars fly-by to gain additional velocity.
Mass spectrometer	An instrument designed to identify gases by measuring the mass of the ions produced when the gas is ionized by an electron beam.
Mission Operations and Data Analysis (MO&DA)	A NASA term that denotes an operational phase of a mission, generally beginning with launch.
Near infrared mapping spectrometer	A spectrometer designed to identify chemical compounds by analyzing wavelengths in the near-infrared region of the electromagnetic spectrum.
Nephelometer	An instrument that determines the size and nature (liquid or solid) of cloud particles and the location of cloud layers.
Net flux radiometer	An instrument that determines ambient thermal and solar energy as a function of altitude.
Neutral mass spectrometer	An instrument used to analyze the chemical composition of an atmosphere.
Orbiter	A spacecraft or mission involving the 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.
Photopolarimeter radiometer	An instrument that measures temperature profiles, energy of an atmosphere, and cloud characteristics and composition.

Pioneer	A series of interplanetary missions (Pioneer 10, 11, 12, and 13), that were launched between 1972 and 1978.
Plasma detector	An instrument that provides information on low-energy particles and clouds of ionized gases in the magnetosphere.
Plasma wave spectrometer	An instrument designed to detect electromagnetic waves and wave-particle interactions.
Probe	An instrumented device designed to gather data during the descent and/or landing on a planet.
Radio propagation	An experiment that measures the minute changes in frequency, power, time delay, and polarization of the spacecraft's radio signals when blocked by a planet, a satellite, the sun, or the solar wind.
Radioisotope Thermoelectric Generator (RTG)	An electrical power generator consisting of a heat source and a system for the conversion of heat to electricity. The heat source contains a radioisotope (such as plutonium-238) that produces heat from its radioactive decay. The heat is converted to electricity by a thermoelectric converter.
Shuttle	A U.S. Space Transportation System vehicle that places 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.
Solid fuel	A solid propellant usually containing both fuel and oxidizer.
Solid-state imaging	An instrument that uses a charge-coupled device (photovoltaic array) to generate images in the visual range of the electromagnetic spectrum.
Spin-scan imager	An imaging instrument that is mounted on a spinning observation platform.

Trajectory	The path traced by a rocket or spacecraft moving as a result of an externally applied force, considered in three dimensions.
Ultraviolet spectrometer	An instrument that studies the composition and structure of an upper atmosphere by analyzing the intensity of ultraviolet emissions triggered by the destruction of complex molecules by solar ultraviolet light.
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-Earth-Earth-Gravity-Assist (VEEGA) trajectory	The latest trajectory for the Galileo mission that requires a gravity assist from a Venus fly-by followed by two gravity assists from earth fly-bys.
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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