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Planetary Exploration Spacecraft Design

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Introduction

Having only begun in the early 1960s, planetary-exploration spacecraft design is a fairly new art[1]. Between 1962 and 1973, NASA designed, built and launched ten spacecraft named Mariner to explore Venus, Mars and Mercury for the first time. In 1962, the Jet Propulsion Laboratory (JPL) launched the Mariner 2 spacecraft[2] (Fig. 1) to explore Venus. In 1965, Mariner 4 flew by Mars and captured the first close-up photos of another planet.

Each year since 1962, at least one planetary-exploration spacecraft has been launched by NASA, the USSR, Japan or the European Space Agency[3]. Two of the best known are NASA's Voyagers[4,5,6] (Fig. 2), which were launched in 1977, two years after NASA's Viking mission[7] sent landers and orbiters to Mars. Today, 24 years after launch, and having completed a tour of Jupiter, Saturn, Uranus and Neptune, Voyager 2 still returns data from a distance of 64 Astronautical Units (AU), where the one-way light time is nearly nine hours. NASA spacecraft have visited every planet in the solar system except Pluto, and orbited Venus, Mars, Jupiter. In 1975, the USSR's Venera 9 and 10 spacecraft sent the first photos from the surface of another planet (Venus); in 1986, the European Space Agency's Giotto spacecraft captured the first detailed photos of a comet's nucleus (Halley's). The NASA/JPL Cassini[8] spacecraft (Fig. 3) is due to enter Saturn orbit in 2004. The NASA/APL MESSENGER[9] spacecraft is due to orbit Mercury in 2009. MESSENGER is being built by the Johns Hopkins Applied Physics Laboratory (APL) as was the Near Earth Asteroid Rendezvous[10] (NEAR) spacecraft (Fig. 4) that orbited and touched down on the asteroid Eros in February 2001. Planetary exploration spacecraft are truly among mankind's most fascinating machines, and their missions are some of mankind's most audacious endeavors.

This article addresses the important elements of planetary-exploration spacecraft (PES) design. Spacecraft elements will be described in some detail, with principal focus on the system design and the technical subsystems. Ground stations, launch vehicles, science, and navigation elements[11] are not addressed. The scope of this article includes those spacecraft that fly by, orbit or land on other planets, asteroids or comets.

Planetary Exploration Spacecraft Design Requirements and Constraints

Introduction

PES design is a process that is driven by the unique nature of planetary exploration missions and their science investigations. Mission and science requirements are used to determine spacecraft system-level requirements, and in turn subsystem requirements, as shown in Figure 5. Basically the spacecraft design is driven by where the mission goes, how it gets there, and what it does. The remainder of this section presents a brief discussion of important mission and system requirements and constraints that drive the design of a planetary-exploration spacecraft.

Mission Objective

The mission objective is to perform scientific exploration and investigation. In order to conduct the desired science investigation, it is necessary to transport the scientific payload to the destination, and provide the payload with power, environmental protection, the proper instructions and orientation for performing measurements, and the necessary communications technology for transmitting the resulting data to Earth. A large complex of people, computers, communication lines, and tracking antennas on Earth is needed to guide and support the mission.

Very High Standards

Two paramount constraints for all missions are that once launched from Earth, spacecraft hardware can never be repaired, and there is very low tolerance for any failure. Because overwhelming media coverage ensures that the world will instantly learn of any problem, no space agency committing public resources to build, launch and operate a PES welcomes even the perception of failure. All of this creates enormous pressure on a PES and its mission to succeed. Consequently, the spacecraft must be designed, built and operated to extraordinarily high standards.

Instruments

A PES fundamental function (what it does) is to transport the instruments needed to perform the science and exploration investigations. Most of these instruments are passive devices that operate in parts of the electromagnetic spectrum, including long-wavelength radio waves, the infrared (IR), visible, the ultraviolet, x-rays, and gamma rays. Some instruments, like radar and LIDAR (light detection and ranging), are active-sensing. The instruments place requirements on the spacecraft such as mass, power, pointing, data rate and data volume. Some instruments place special requirements on the PES. Spacecraft carrying sensitive magnetometers must be "magnetically clean," i.e., designs must specify special electronic parts, shielded components, and sometimes equipment to generate and maintain offsetting magnetic fields. To avoid receiving its own spacecraft emissions, for example, a magnetometer may need to be flown at the end of a long boom; this greatly affects the attitude control-system design. A gamma-ray-detector onboard means that overall spacecraft emissions must be checked, and components altered or removed so their output does not swamp the target planet's signals.

Planetary Protection

Planetary protection is a unique requirement for planetary spacecraft. It means protecting another planet's environment from Earth's biological contamination, and protecting Earth's environment from extraterrestrial contamination. Usually applied to landers and critically important for those missions whose objective is to return a sample of another planet to Earth, it also applies to orbiters whose orbit may someday degrade, causing the spacecraft to hit the surface. To illustrate, consider the Mars orbiter NASA currently plans to launch in 2005. The planetary protection requirements for this mission are: 1) all flight hardware is to be assembled and maintained in class 100,000 clean rooms (or better), 2) the probability of an impact of Mars by any part of the launch vehicle (including the upper stage) that leaves the vicinity of Earth must not exceed 10-4 and, 3) the probability of an impact on Mars by the orbiter due to all causes must not exceed 0.01 for the first 20 years after launch and 0.05 for the succeeding 30-year period. In order to meet part of the third requirement, the flight system must be designed with a reliability for the mission (launch through the attainment of the final orbit) better than 0.99. In order to meet part of the third requirement above, the spacecraft-ballistic coefficient must also be also be taken into consideration.

Solar System

The most important influence on the design of a planetary exploration spacecraft is the solar system itself. A spacecraft designed to travel the solar system must successfully operate in the solid particle and radiation environments of the solar system. The spacecraft must operate far from Earth and at a Sun range greatly different than 1 AU. The large Earth range implies a significant light time for signals sent to and from the spacecraft; long trip times to the final destination; and the need for precise navigation. Launch dates for PES are inflexible and may occur only once every two years (or less frequently) and are set by the well known, but totally inflexible motion of the planets around the Sun.

Rigid and Infrequent Launch Windows

Solar system dynamics are well known and totally fixed, making for rigid, inflexible and infrequent launch windows separated by many years—even decades. There is enormous pressure to get interplanetary missions to the launch pad on time because missing a window results in intolerable consequences for missions and careers alike. In the case of Mars, for example, a mission may have to wait two years for the next opportunity. Missions to the outer planets may wait much longer. The minimum trip time alignment of the planets Jupiter, Saturn, Uranus and Neptune that the Voyager 2 spacecraft used occurs approximately once every 175 years. In contrast, if an Earth-orbiting spacecraft arrives late for a launch window, another one will open the following week or month. Compared to a typical Earth orbiter, a planetary spacecraft's launch opportunity are very infrequent, and the consequences of failure are especially severe. This consequence of failure creates a greater need for high reliability that is usually implemented through greater robustness in design (parts quality, fault protection and use of redundancy).

Round-Trip Light Time

An important spacecraft-design constraint is round-trip light time—the minutes or hours a distant spacecraft's signal needs to reach Earth, plus the control-signal return time. Due to the solar system's vast expanse, a typical Earth-to-PES distance is usually many orders of magnitude greater than the distance from Earth to an Earth orbiter. A PES at 1 AU from Earth, for example, is 4200 times farther away than a geosynchronous Earth orbiter (GEO), which receives a ground signal from Earth in only a tenth of a second. A spacecraft at Mars may be as much as 2.5 AU from Earth—a one-way, light-travel time of 20 minutes. At Saturn, Cassini's maximum distance to Earth requires a one-way, light-travel time of over 1.5 hours. Despite traveling at the speed of light, the considerably longer time required for PES radio signals to reach Earth must be considered by the spacecraft designer.

To minimize mission risk so it is similar to an Earth orbiter, distant spacecraft must operate more autonomously, especially regarding fault detection and recovery. Long round-trip light time affects how planetary spacecraft are commanded. An Earth orbiter can wait for a command signal before it transmits its recorded telemetry; a planetary spacecraft cannot. Spacecraft performing split-second events, such as landing on Mars, cannot afford to wait for a command to be acknowledged before another is sent. For example, if while executing split-second events, like entering Mars' atmosphere, a spacecraft transmits a distress signal, Earth would receive it only after the probe is on Mars' surface—too late for ground controllers to help.

Earth Range

A spacecraft's telecommunications subsystem is especially driven by a planetary explorer's large Earth range. The strength of the received signal is inversely proportional to the square of the range. The power per unit area received from a GEO spacecraft is 4200 squared or 72db larger than that from the planetary spacecraft at a range of 1 AU from the Earth. To receive the low-strength signals, NASA-built special ground stations collectively called the Deep Space Network[12] (DSN, (Fig. 6). A unique asset on an international scale, and tracking planetary spacecraft from many countries, the DSN receiving network has special-interface requirements for planetary spacecraft. Because navigating interplanetary space requires extremely accurate clocks, the DSN uses a hydrogen-maser-based frequency reference with an accuracy equal to the gain or loss of 1 second in 30-million years. The maser is a reference that generates an extremely stable uplink frequency, which the spacecraft uses, in turn, to generate its coherent downlink.

Even with the DSN, a planetary probe's uplink- and downlink-data rates are lower than an Earth orbiter. If a planetary spacecraft is turning very quickly due to a mission need, or tumbling because of a fault, low-uplink rates can preclude commanding. Due to high-signal strength, an Earth orbiter in nearly any attitude can receive a command, but distant planetary probes must be in specific attitudes or they will not receive the signal. A limited-downlink rate can strongly drive data storage, compression and the optimal recording of data. Also, a limited downlink rate may mean a spacecraft can transmit only a small part of the data that its instruments could produce.

Mission Energy and Trip Time

The destinations for planetary spacecraft are energetically a "long way from earth." The mission energy manifests itself both in terms of the required change in spacecraft velocity (known as delta-V) for departure from Earth and after launch but also in trip time to the destination. Because the required mission energies are so large, most planetary mission trajectories are "minimum energy" trajectories[13]. A consequence of these "minimum energy" trajectories and the vast distances are long trip times to the destination. The largest delta-V for Earth orbiting spacecraft is normally required by a geosynchronous communication spacecraft where the delta-V required to go from low Earth orbit (LEO) to GEO is about 4200 m/sec. The total delta-V beyond LEO for some typical planetary missions are as follows. For a low, circular Mercury orbiter where the trip time is about four years, the required delta-V is 7000 m/sec. A direct 0.4 year trip to a low Venus orbit requires about 6900 m/sec. For a Pluto orbiter with a 20-year trip time, 15,000 m/sec is required. Usually, part of this delta-V is supplied by the launch vehicle for both the Earth orbiters and planetary spacecraft. Several of these planetary missions have not been performed because the delta-V, trip time-combination is so large.

Because of the large delta-V for many planetary missions, methods besides traditional chemical propulsion have been developed, such as electric propulsion systems and the use of the target body atmosphere to aid in capture at the planet. Aerobraking[14,15], as this is known, is a technique wherein the spacecraft is deliberately flown into the top of the target planet's atmosphere. There the drag on the spacecraft acts like a brake and spacecraft energy is dissipated. Aerobraking uses almost no propellant to provide delta-V to change the kinetic energy of the spacecraft. Aerobraking was used by the NASA/JPL Mars Global Surveyor[16] spacecraft (Fig. 7), and will be used by the Mars Odyssey[17] spacecraft (Fig. 8), which will arrive at Mars in 2001.

Long-trip times and minimum-energy trajectories drive the requirement that planetary spacecraft be extraordinarily reliable. While some Earth orbiters may live as long as fifteen years, their operations begin within only a few weeks. But for many planetary spacecraft, missions do not begin until they reach their target, which could take years. For example, Voyager 2 traveled 12 years before its successful encounter with Neptune. The Cassini probe must travel for 6.6 years before its Saturn orbital operations begin. So, it is many years after launch that these spacecraft maneuver for orbit insertion, and open into their final mechanical configuration. The ship's mechanisms, components and instruments must remain workable during those years traveling through space and when activated, perform perfectly.

Extended missions also affect spacecraft operations. For example, when cruise time is lengthy, additional operational modes, software and procedures are needed. Also, because of personnel turnover during missions measured in decades, retraining is absolutely critical if fatal errors are to be avoided in the mission's end game, when the people who designed the final procedures have moved on. To reduce peak-year costs, multi-year mission planetary encounter-command sequences are not developed until after launch. Therefore, spacecraft design must accommodate new flight software that will be tested "on the fly." Changes in data-systems technology also affect lengthy missions, and vice versa. Ground-system components, for example, may be upgraded during the mission. On the positive side for long-cruise-time missions, there is time to diagnose and hopefully correct any errors before the primary mission begins.

Space Radiation Environments

Because planetary-spacecraft environment is very different from an Earth orbiter, it also impacts the system. Although usually stable, this distant environment is uncertain, and one of the mission goals may be to learn more about it. To keep the risk level close to that of an Earth orbiter, a distant mission may require more environmental analysis and margin. PES design must accommodate space radiation and solid particles. The three types of space-radiation environments are planetary-trapped radiation, galactic-cosmic radiation, and solar-energetic particles.

Because the trip through them is short, spacecraft are not affected by Earth's radiation belts, but other-planetary belts can be a serious threat. Even short gravity-assist passages through Jupiter's system, for example, will expose the spacecraft to most of a mission's total-radiation dose. Also, heavy-ion fluxes will disrupt critical-mission functions with single-event effects (SEE).

Galactic cosmic radiation (GCR) is composed of high-energy nuclei. The Earth's magnetic field provides some shielding against this radiation for spacecraft in low-to-medium Earth orbits. Even so, the radiation flux associated with GCR in interplanetary space is low and does not contribute significantly to the mission total-ionizing dose, but sufficient heavy ions are present in the GCR populations to create a SEE threat to some electronic parts throughout the mission.

Solar-energetic particles are also attenuated by the Earth's magnetic field, but in interplanetary space, fluxes due to a given solar event may be 2-3 times more intense than near Earth and thus present both a total dose and SEE threat. When they are outside Earth orbit, solar-event fluences dissipate in inverse proportion to the square of the heliocentric distance. So, outer-planet missions are reasonably safe. But inside 1 AU, it is a different story. For missions visiting Venus or Mercury, the hazards of solar-event radiation can be considerable. For instance, even a moderate solar event can incapacitate a spacecraft passing within only a few radii of the Sun.

The solid-particle danger to interplanetary spacecraft has two origins: micrometeroids (particles orbiting the Sun), and dust (particles orbiting other solar-system bodies). Only in a mission's immediate post-launch phase is artificial debris encountered. Although there are few particles in interplanetary space, encounter velocities are high (~15-50 km/s) and can be very damaging. The nature of the encounter dictates the velocity. Because Cassini will go into a Saturn orbit, its encounter velocity with the planet's ring particles is much lower than Voyager's speed when it passed close to Saturn to obtain a gravity assist.

Sun Range

Sun range (distance to the Sun) especially affects a PES power, and thermal-control subsystems. Widely varying spacecraft-Sun distances—especially when they change during a mission—dramatically impact design. For example, Cassini flew by Venus (0.6 AU) for gravity assists, and headed out to Saturn (10 AU) to conduct its prime mission. A Mercury orbiter[18] encounters a huge thermal range: its illuminated side receives 10.6 suns (mainly short-wave IR), while the other side sees 8.5 suns (long-wave IR reflected from the planet's surface). And a few hours later in solar eclipse, the orbiter will see no "suns" on either side.

Sun-range effects on the power subsystem are directly the opposite, depending upon whether the mission destination is less than, or greater than 1 AU. Spacecraft going to the inner planets have the problem of their power output increasing with mission time, up to a point where solar cells developed for Earth orbiters are no longer usable without special coatings, or they are not usable at all. The spacecraft may solve its excess-heat problem by pointing away from the Sun or shunting the excess power and radiating the excess as heat.

The opposite problem is true for an outer-planet-bound spacecraft because its solar-array power gradually drops off and finally stops. Special solar arrays designed for low-light, low-temperature conditions are required. In some cases, a PES will use a Radioisotope Thermoelectric Generators (RTG) for electric-power production. Another problem for out-bound spacecraft: unless "makeup heat" is provided, or heat is conserved, components may cool below safe-operating temperatures. Experience dictates that outer-planet missions must invest more of their development time and money in power-efficient technologies.

Navigation

Due to the size of the solar system and the motion of the planets, a planetary-exploration spacecraft must be carefully navigated to its destination. Radiometric data can be used to determine spacecraft position relative to a planet—to within a few kilometers at best. Velocity data is accurate to within a few tenths of a mm/sec. Non-gravitational acceleration caused by unplanned or un-modeled spacecraft accelerations like outgassing, leakage or uncoupled attitude-control maneuvers can greatly affect spacecraft navigation. Acceleration due to these forces must be kept to within a few mm/sec^2, accurately modeled, and reported. In 1999, perhaps due to an error modeling these forces, engineers believe that Mars Climate Orbiter[19] (Fig. 9) entered Mars atmosphere too low to achieve orbit and probably burned up.

Planetary Exploration Spacecraft Subsystem Design

Subsystems are individually tailored and integrated to implement the overall-system design[20]. They include: Attitude Control, Commanding and Data Handling, Mechanical Devices, Power, Propulsion, Structure, Telecommunications, and Thermal. Table 1 presents the subsystem characteristics of several planetary-exploration spacecraft.

Structure

This subsystem includes spacecraft primary and secondary mechanical and structural members that support and align all flight subsystems and equipment during ground handling, launch and flight. Structure also protects against natural and induced environments such as vibration, meteoroids, radiation, and electromagnetic interference. Generally, an Earth-orbiting and a planetary spacecraft-structure subsystem are alike.

Thermal

The thermal subsystem heats or cools spacecraft components in order to maintain them within operating and non-operating temperature ranges. This function includes meeting special temperature requirements of components such as batteries, and cryogenic instruments. Temperature control must be effective throughout the mission's prelaunch, launch, cruise, and operational phases.

Stated simply, a planetary spacecraft's thermal-design strategy is: Use passive components whenever possible because they use less power, operate more simply, and are thus more reliable than active ones. The idea is to minimize temperature sensitivity due to external and internal heat fluctuations, and emphasize passive techniques (e.g., blankets, radiators, coatings) over active ones (e.g., heat pipes, fluid loops, thermostatically controlled heaters).

Earth orbiters have the “in Sun” and “in eclipse” design points, while planetary orbiters have “in Sun” and “in eclipse” conditions that may vary dramatically over the course of the mission due to the change in Sun range. To confidently design the thermal subsystem for a planetary mission, at least additional thermal analyses and testing are required. In addition, for those missions going to less than 1 AU, available thermal-control materials and paints may be limited, and entirely new ones may need to be developed. A requirement to keep large amounts of propellant at a given temperature during a long cruise between launch and orbit insertion may be the main power-and-thermal design driver.

All spacecraft use multi-layer blankets to provide thermal control. For PES, the multi-layer thermal-insulation blankets also provide some protection against micrometeoroid impacts. They are made with Kapton, Kevlar, or other fabrics strong enough to absorb energy from high-velocity micrometeoroids before they damage spacecraft components. Impact hazards are greatest when crossing the ring planes of the Jovian planets. Voyager recorded thousands of hits in these regions, fortunately from particles no larger than smoke particles. Spacecraft sent to comets, such as Stardust[21], carry massive shields to protect from hits by larger particles.

Mechanical Devices

Mechanical devices perform functions like separating a spacecraft from its launch vehicle; deploying booms; articulating high-gain antennas and solar arrays; jettisoning aeroshells and deploying parachutes; releasing instrument covers; and controlling fluid flow in propulsion and pressurization systems. These devices must operate with essentially 100% reliability for many years after launch. Earth orbiters achieve their final spacecraft mechanical configuration early in their lifetime. But, because cruise time to a mission site is very long, it may be many months or years before a PES assumes its final mission configuration. The final deployment of the Mars Observer spacecraft[22] (Fig. 10) solar panels, high gain antenna boom and a science-instrument boom were to have occurred after insertion at Mars, nearly one year after launch.

The Cassini[23] spacecraft will release a large Titan atmospheric spacecraft seven years after launch. There is always concern that mechanical-actuation devices may be less reliable after a long time in space. Because these devices are all candidates for single-point failures, a design remedy is to add redundant actuators. Mars Pathfinder, which successfully deployed Sojourner rover (Fig. 11) on Mars, depended on 42 pyrotechnic events during its successful atmospheric entry, descent and landing. Design practices emphasize large strength or force margins, redundancy where practical (e.g., bearings within bearings), vacuum-compatible materials and lubricants, and special attention to thermal-expansion-and-contraction effects. All mechanical devices are extensively tested to verify margins and lifetime, and intentional "fouling" tests are conducted to achieve extra confidence. A mechanical-actuation system successfully operated on an Earth orbiter may fail to work on a planetary spacecraft. An example is the Galileo (Fig. 12) spacecraft's high-gain antenna failing to completely open. While the actual cause will never be known, extensive prelaunch handling—rather than the long-storage time en route to Jupiter—may have been the culprit.

Command and Data-Handling

The brain and memory of a spacecraft is the command and data-handling subsystem (C&DH). Consisting mainly of computers, memory, and input/output devices, it provides the spacecraft's time reference. C&DH also performs real-time and preprogrammed functions like decoding ground commands; distributing discrete and coded commands to subsystems; responding to onboard-generated events; and collecting, managing and storing science and engineering data. Primary-design considerations include processor speed, quantity and access-speed of memory, as well as fault-detection-and-correction techniques. In some cases, onboard processing of optical-navigation images may be required to reduce the quantity of data transmitted to Earth, or to reduce response time for critical events. The need for autonomous-fault diagnosis and recovery on planetary spacecraft requires that designers develop, design, and validate additional onboard software. And in turn, fault-protection software needs computer memory, processing power, and additional telemetry data.

Compared with an Earth orbiter, planetary spacecraft must have additional intelligence and autonomy to monitor and control itself. The PES is always a great distance from home, is tracked as little as once per day or once per week and cannot communicate with Earth during certain periods. For example, during superior conjunctions (when the spacecraft and Earth are on opposite sides of the Sun), autonomous fault-protection software must intervene in case of an onboard failure. Light time, and tightly constrained tracking schedules prohibit ground teams, who control and monitor the spacecraft, from immediately responding to onboard anomalies. When failures occur, C&DH fault-protection algorithms must detect them and in the case of a communications interrupt, re-establish contact with Earth. A spacecraft may have many different fault-protection monitoring algorithms running simultaneously and must be prepared to request C&DH to take action. The command-loss timer, for example, is reset to a predetermined value, e.g., one week, each time a command arrives from Earth. If the timer runs down to zero, it is assumed that the receiver or another component in the command string suffered a failure. The fault protection response may then be to switch to redundant hardware to re-establish radio contact with Earth.

Other fault-protection responses include requesting safe mode; shutting down or reconfiguring components to prevent damage; or performing an automated, methodical search to reestablish Earth-pointing in order to regain communications. While entering safe mode may temporarily disrupt science gathering, it provides reliable spacecraft-and-mission protection. ROM usually carries a minimal set of safe-mode instructions (the Magellan spacecraft [Fig. 13] ROM contained only 1 KB of this code); commands can hide in ROM from the worst imaginable scenarios of runaway-program executions or power outage. More intricate safe-mode and fault-protection routines (e.g., "contingency modes"), and parameters for use by the ROM-code, typically reside in RAM where they can be updated as needed during the mission lifetime.

Attitude Control

This subsystem keeps spacecraft motions stable and precisely points and orients the spacecraft (or single instruments) despite gravity gradients, propulsion-system torque, solar pressure, and sometimes micrometeoroid impacts. Precise pointing is important because the high-gain antenna has to acquire Earth; science instruments must collect data; thermal radiators have to be properly positioned; Sun-and-star sensors must provide attitude references; and to generate maximum power, solar panels have to be Sun-oriented. The spacecraft must be pointing in the correct direction in order to make precise trajectory-control maneuvers.

Due to expending large amounts of propellant, the attitude-control subsystem design must take into account the resulting dramatic changes in a spacecraft's inertia properties as a function of mission time. Because a PES is not orbiting Earth, the attitude-control subsystem must operate differently. Ships orbiting other planets sometimes use horizon sensors, so Earth-horizon sensors must be adapted to a different atmosphere, or no atmosphere. GPS receivers cannot be used for orbit or attitude information. Without Earth as an attitude reference, planetary spacecraft become highly dependent on celestial sensors and celestial-attitude determination. Without a well-characterized, adequately strong magnetic field, magnetic-torque rods cannot be used for attitude maneuvers, or to desaturate reaction wheels. While planetary spacecraft may be sent to orbit planets that have a magnetic field (Jupiter), usually the magnetic field is not well enough known to be used for attitude determination and control purposes.

Because of the various forces acting on it, an unstabilized spacecraft will acquire rotational motion, and tumble in a chaotic fashion. As with Earth-orbiting spacecraft, a PES may be spin stabilized or 3-axis controlled. Spinners that have been used include the Pioneer 10 and 11 spacecraft in the outer-solar system, Lunar Prospector (Fig. 14), and the Galileo[24] orbiter spacecraft. The gyroscopic action of the rotating spacecraft mass is the stabilizing mechanism. Propulsion-system thrusters are fired only occasionally to make desired changes in the spin-stabilized attitude. The proper attitude-and-spin rate for two atmospheric probes—one launched into Jupiter's atmosphere by Galileo, the other to be sent into Titan's atmosphere by Cassini—are imparted by the mother ship.

Alternatively, a spacecraft may be designed for active 3-axis stabilization. One method is to use small propulsion-system thrusters to continuously nudge the spacecraft back and forth within a dead-band of allowed attitude error. Voyagers 1 and 2 have been doing this since 1977, and have consumed about 70 kg of their 106 kg of propellant as of April, 2001 and are using propellant at a rate of about 7 grams per week[6]. Another method is to use electrically-powered reaction wheels, as on Mars Global Surveyor and the recently launched Mars Odyssey. Reaction wheels provide a means to trade angular momentum back and forth between spacecraft and wheels. To rotate the vehicle in one direction, you spin up the proper wheel in the opposite direction. To rotate the vehicle back, you slow down the wheel. Excess momentum that builds up in the system due to external torques, caused for example by solar-photon pressure or gravity gradient, must be occasionally removed from the system by applying torque to the spacecraft and allowing the wheels to acquire a desired speed under computer control. This is done during maneuvers called momentum desaturation, or momentum-unload maneuvers.

Telecommunications

This subsystem provides communication to and from Earth for the purpose of spacecraft navigation, commanding, and telemetry. Its hardware includes antennas, transponders, and amplifiers. The key functions are signal modulating, demodulation and some types of data encoding. The key-performance parameter is the number of bits per second (bps) that can be transmitted. Among other parameters, the data-rate performance is proportional to transmitter power, the area of the transmitting and receiving antennas, and the square of the transmitting frequency. While planetary-exploration spacecraft use the same Ka-, S-, and X-frequencies as other spacecraft, there are special frequency allocations for deep space that are different than for Earth-orbiting spacecraft[25]. Over the past 25 years, there has been a trend toward higher frequencies for spacecraft telecommunications from S to X, and now to Ka-band (32 Ghz). Researchers are developing optical-communication systems, which provide greatly increased performance because of their higher frequency. Current state of the art interplanetary-data transmission rate over Mars range (~2 AU) is about 85Kbps, but currently NASA is considering a Mars mission in 2005 that may use a data rate as high as 4Mbps.

In addition to the primary function of transmitting data to Earth and receiving commands, the telecommunications subsystem is an important element in the navigation system for PES and sometimes is used as part of a scientific investigation. Due to the extreme distances over which planetary spacecraft must be navigated, highly accurate radio-metric data are required. To obtain typical accuracy requirements of a few meters for range measurements, and 0.1 mm/sec for Doppler, a well-calibrated coherent ranging transponder is needed. Radio-science experiments use the spacecraft radio and the DSN together as their instrument, rather than using only an instrument aboard the spacecraft. Radio-science experiments record the attenuation, scintillation, refraction, rotation, Doppler shifts, and other direct modifications of the radio signal as it is affected by the atmosphere of planets, moons, or by structures such as planetary rings or gravitational fields. From these data, scientists are able to derive a great deal of information such as the structure and composition of an atmosphere, and particle sizes in rings.

The receiver-acquisition-and-tracking characteristics are unique for planetary spacecraft. Compared to typical Earth orbiters, the receiver threshold is very low, the loop bandwidth is very narrow and the received-signal strength at the ground station is very low for planetary spacecraft, typically as low as -150 dbm. While the DSN provides the largest, most sensitive ground stations available in the world, closing the telecommunications link (both up and down) is still so difficult that the margin left in the link for planetary spacecraft is far less than the typical 10 db used on Earth orbiters. Planetary-exploration spacecraft use high-gain antennas for communications, which must be pointed to within a small fraction of one degree. The stringent requirements on the telecommunications link for planetary spacecraft have caused the development of sophisticated channel-coding techniques. Coding is a technique using logic and mathematics to help ensure error-free data transmission. One coding scheme most interplanetary spacecraft use is a forward-error correction scheme called convolutional coding with Viterbi decoding. Another coding technique is Reed-Solomon. Reed-Solomon coding adds bits, and is generally imposed prior to the convolutional code. A recent advance in coding is called turbo code, which may be used on a mission to Mars in 2005.

Power

This subsystem generates, conditions, controls, and distributes onboard power. Power sources may include solar-cell arrays, RTGs, or batteries. Electrical power must be conditioned for particular end users, distributed, made stable, and safely controlled to protect the entire system from power failure. Experience shows that a PES requires a few hundred watts up to about 1 kW of electricity to power all the computers, radio transmitters and receivers, motors, valves, heaters, data storage devices, instruments, a host of sensors, and other devices.

For a PES going beyond about the orbit of Jupiter, the first power-design question is, whether to use RTGs or solar arrays. This decision is based upon the Sun range of the mission, the state of readiness of the various power-source options, the acceptable level of mission risk, safety considerations and the amount of resources (time and dollars) available to the mission. If RTGs are chosen, spacecraft design dramatically departs from Earth-orbiter design. Currently RTGs contain several kilograms of an isotopic mixture of the radioactive element plutonium in the form of an oxide pressed into a ceramic pellet. The primary constituent of these fuel pellets is the plutonium isotope 238. Plutonium 238 emits low-energy alpha particles (which can be stopped by a sheet of paper) and very small amounts of gamma radiation. This, coupled with its relatively long half-life (87.7 years) and high-melting point (~2300 K), makes it the isotope of choice, even though it is expensive and has a much lower-power density (4 W/g) than isotopes of cesium, cobalt, and polonium.

The natural radioactive decay of the plutonium produces heat (RTGs do not use fission or fusion), some of which is converted into electricity by an array of thermoelectric thermocouples. Thermoelectric-conversion technique does not employ moving machinery components, but instead, uses the phenomenon of temperature-induced current flow in materials (Seebeck effect). In this system, a pair of dissimilar semiconductor materials (silicon-germanium) with each end at different temperatures is joined in a closed circuit to produce a voltage. Unfortunately, the conversion efficiency is quite low (typically 5-8%) and RTGs radiate to space about 20 watts for every watt of electric power produced. The spacecraft must accommodate this thermal radiation as well as the nuclear-radiation environment. Although gamma rays and neutrons from RTGs pose no SEE threat, they contribute a major part of the total dose to nearby electronic components. These radiation forms are considered "unshieldable" in the sense that no amount of shielding that would be practical on a spacecraft is sufficient to be effective against these particles. Often some of the IR sensing science instruments can be "blinded" by the warm RTG, and a RTG shade is required. Sometimes a cooling system must be included in order to keep the spacecraft from overheating when enclosed in the launch vehicle. The RTG will probably be required to be conductively isolated from the rest of the spacecraft unless, the designer tries to make use of the RTG waste heat to keep the spacecraft warm, which is a good idea but makes the thermal design of the spacecraft much more complicated than that of an ordinary Earth orbiter.

Besides complicating the design, RTG-powered spacecraft must consider important environmental and safety issues. The National Environmental Policy Act, for example, requires that an impact statement address nuclear-safety risks. And, Earth-gravity-assist missions must mitigate the possibility of inadvertent Earth reentry, and prove that those risks are negligible.

Propulsion

The propulsion system provides thrust that is used to maintain 3-axis stability, control spin, execute maneuvers, and make minor adjustments in trajectory. The propulsion subsystem includes the engines, propellant tanks, pressurant tanks and associated valves and plumbing. The larger engines may be used to provide the large torques necessary to maintain stability during a solid-rocket motor burn, or they may be the only engines used for orbit insertion. Smaller thrusters, generating between less than 1 N and 10 N, are typically used to provide the delta-V for interplanetary trajectory-correction maneuvers, orbit-trim maneuvers, reaction-wheel desaturation maneuvers, or routine 3-axis stabilization or spin control.

The requirements and constraints of planetary-exploration missions cause the propulsion subsystem designer to pay attention to several special issues. Because navigation is so difficult for planetary missions, un-modeled accelerations such as those from outgassing, and leakage must be avoided and thrusters should be arranged to provide attitude-control torques in coupled pairs to avoid any translation delta-V. For some missions, science objectives drive the choice of propulsion system. Sensitive optical surfaces, cryo-cooled sensors, and low-temperature thermal radiators are vulnerable to contamination produced by the propulsion system. Spacecraft using such devices require propulsion systems that do not exhaust condensable species that can accumulate on these sensitive surfaces. In some cases, a particular propulsion option is eliminated because a spacecraft instrument is designed to detect the very same chemical species that are present propulsion-system exhaust.

Trajectories used for some planetary missions often require large maneuvers en route, which cause the primary propulsion system to be used many times with a series of large "burns" required for orbit insertion which can occur years after launch. The primary engine used to deliver the mission delta-V on a planetary spacecraft may have to operate for up to 10 hours, and perform 200 cycles compared to a similar engine used on an Earth orbiter that may only need to operate for 2 hours, and only 5 cycles. For a planetary spacecraft, the propellant supply and pressurization system-life requirement may be many years. Earth orbiters, such as GEO-communication spacecraft, use most of their propellant during the first few weeks of the mission after which the bi-propellant-main-engine and pressurization system are isolated for the remainder of the mission. The long-life requirement for the propellant-supply-and-pressurization system for planetary spacecraft require careful consideration of pressurant leakage and propellant/tankage-material interactions which can lead to blocked propellant lines. To reduce the probability of propellant-line blockage, the Galileo spacecraft bi-propellant subsystem is used on a routine basis to reduce the accumulation of corrosion products[26]. The requirement for a long storage in space for the propulsion subsystem can drive the requirement for special isolation between the propellants that causes additional pyro-and-latch valves to be used. Lack of proper design and isolation within the bi-propellant-pressurization system on the Mars Observer spacecraft is thought to be a leading cause of its failure[27]. The Magellan spacecraft, which orbited Venus, used a large solid-rocket motor (SRM) for orbit insertion. The long duration of "storage" in space caused concern about whether the SRM would ignite and burn properly. Earth-orbiter SRMs are fired usually within days of launch.

Due to the large required delta-V of many planetary-exploration missions, electric propulsion using ion engines has long been viewed as an attractive alternative to chemical propulsion. Ion propulsion using xenon propellant has been demonstrated on the NASA/JPL Deep Space 1 spacecraft[28] (Fig. 15). Ion propulsion[29,30] provides an exhaust velocity about ten times larger than a traditional chemical-propulsion subsystem, and therefore use only about one-tenth the amount of propellant to provide the same delta-V. While there is a significant savings in propellant, electric-propulsion systems require additional power generating-and-conditioning equipment that offsets to some degree the savings in propellant mass. Interplanetary spacecraft using ion-propulsion systems can undertake the very high delta-V missions that would be prohibitively massive and therefore expensive using traditional chemical-propulsion techniques.

PES Principles and Margins

The preceding pages have described the key requirements and constraints on planetary-exploration spacecraft, and how those requirements and constraints influence the design of the spacecraft. While the design of planetary-exploration spacecraft is a relatively young art, the practice of this art and the struggle against the requirements and constraints for 40 years and about 20 design cycles has enabled some detailed technical-design principles[31] to be identified. These design principles, being implemented at NASA's Jet Propulsion Laboratory, have their origin in the need for planetary-exploration spacecraft to be very reliable due to their long and unique missions. This section also includes design margins[31] that have been developed in order to increase the probability that the spacecraft will be ready to launch (with a high degree of certainty) during the inflexible launch window imposed by solar-system celestial mechanics. In many cases, these principles have been developed in response to past failures[27,32,33].

Principles applied during the design phase that ensure long-lived spacecraft successfully complete very challenging missions include:

- No single electrical and/or mechanical failure shall result in the loss of the entire mission.
- Inflight routine, critical-hardware power cycling shall be avoided.
- Mission-critical data (i.e., fly-by science, orbit insertion, etc.) can be simultaneously recorded onboard and transmitted.
- Thermal design shall keep piece-part, silicon-junction temperatures below 110°C (assuming a 70°C mounting-surface temperature) for circuit design and packaging.
- Electronic-hardware design shall be power on-off, temperature-cycling survivable and/or solar exposure cycling of three times the number of worst-case expected mission cycles with worst-case flight-temperature excursions. Prior to having a mission estimate, the equivalent of 10,000 cycles with a 15°C delta-T for new/inherited design hardware shall be used.
- The prime-power distribution hot-and-return lines shall be DC-isolated from spacecraft chassis by at least 2 K ohms. (This ensures a single-fault; chassis short anywhere in the distribution system among power source, electronics or user loads does not pose a catastrophic failure.)
- Prime-power on/off switching of electrical loads shall be done by "simultaneously" switching both hot-and-return sides. This ensures total-load removal (no possible ground-return sneak paths) in case of power-related faults.
- Mission-critical deployable design (e.g., solar arrays) shall demonstrate a margin of at least 100% under worst-case conditions, particularly cold, stiff cable bundles, vacuum versus air, and coefficient-of-friction effects.
- Mission-critical separation design (e.g., launch vehicle, probe release) shall demonstrate a margin of at least 100% under worst-case conditions.
- Mission-critical mechanisms and actuator design shall demonstrate at least 100% margin for range-of-motion and the end-of-life stage under worst-case conditions, including restart from within any range-of-motion position.
- All electronic-parts radiation capability shall be at least twice the expected end of nominal-mission environment.
- A minimum pre-launch power-on operating time shall be established for all electronics as follows:
    - Unit level prior to spacecraft integration: each electronic assembly, including each side of a block-redundant element, shall have at least 200-hours operating time.
    - System-level prior to launch: each single-string electronic assembly shall have 1000-hours operating time. Each side of a block-redundant element shall have at least 500-hours operating time with a goal of 1000 hours.

Planetary Exploration Spacecraft Operation Principles

These principles address the most common-and-critical issues associated with operating a planetary-exploration spacecraft far from Earth for many years with only a single opportunity to perform its unique mission.

- All flight-command sequences shall be tested on a high-fidelity, flight-like system-test bed and all anomalies understood and corrected prior to sequence-uplink transmission.
- After initiation, mission time-critical operations shall not require "ground-in-the-loop" commanding to enable successful operation/completion.
- Launch-sequence completion shall leave the spacecraft in a ground-commendable, safe state requiring no "immediate" time-critical ground commanding to assure health/safety.
- After inflight turn on, the downlink-RF transmitter shall not be turned off during nominal-flight operations, but shall remain powered during the entire mission except for momentary power cycling via system-autonomous, fault-protection responses.
- Power cycling mission-critical hardware shall be avoided.
- Prime selected hardware elements shall remain in use for all operations.
- Swapping to redundant-hardware elements shall be limited to fault-recovery actions to assure health/safety.
- Stored-critical data (e.g., launch, fly-by science, orbit insertion, entry/descent and landing, etc.) shall be protected from loss in the event of selected anomalies, (e.g., transient-power outage) and shall be transmitted to Earth as soon as practical.
- Mission-critical events (e.g., launch-vehicle separation, deployments, etc.) and deployables verification shall be available via real-time telemetry.
- Telemetry-and-command capability shall be available throughout the mission in normal cruise-pointing attitude, and during special cruise-phase mission/system activities (e.g., long duration deep-space trajectory-correction, maneuvers, propulsion mission-critical pyro-device actuations).
- During non-mission-critical cruise periods following a fault condition, the flight-protection response shall at a minimum autonomously configure the spacecraft to a safe, quiescent, ground-commandable state, preferably transmitting engineering status but a least an RF-carrier downlink signal.
- During critical-mission activities (e.g., launch, orbit insertion), the flight fault-protection response shall autonomously reestablish the needed spacecraft functionality to permit safe, reliable and timely mission-critical activity completion.

Design Margins

These are intended to keep the spacecraft design, build and test program on track to meet the launch date. Design margins must be large enough to accommodate design uncertainties/unknowns and still enable design changes with minimal system-wide effects.

- Spacecraft system-level mass margin shall be at least 30% at the project start, 20% at project preliminary design review (PDR), 10% at critical-design review (CDR), 5% at assembly, test, and launch operations (ATLO) readiness and 2% at launch.
- The spacecraft-system-level power margin for cruise, mission critical, and safing modes shall be at least 30% at project start, 20% at project PDR, 15% at CDR, and 10% at ATLO Start.
- At launch, there shall be at least 10% predicted power margin for mission-critical, cruise, and safing-operating modes.
- At the start of the spacecraft design, the computer throughput and memory capability shall exceed estimated requirements by at least a factor of 4.
- The nominal Deep-Space link margin shall be at least 3 db.
- Deep-Space links with extreme-geometry conditions, surface-to-orbit links, or surface-to-surface links shall consider 10db or more margins, depending on the nature, complexity and scope of design uncertainties.

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FIG. 1. Launched in 1962, Mariner 2 became the first spacecraft to fly by another planet, studying Venus atmosphere and surface. During its 3-1/2-month journey to Earth's neighbor, the craft made the first-ever measurements of the solar wind, a constant stream of charged particles flowing outward from the Sun. It also measured interplanetary dust, which turned out to be scarcer than predicted. In addition, Mariner 2 detected high-energy charged particles coming from the Sun, including several solar flares, as well as cosmic rays from outside the solar system. As it flew by Venus on December 14, 1962, Mariner 2 scanned the planet with infrared and microwave radiometers, revealing that Venus has cool clouds and an extremely hot surface. Mariner 2's signal was tracked until January 3, 1963. The spacecraft remains in orbit around the Sun.

Table 1. System Characteristics of Some NASA / JPL Spacecraft

Project and Launch Year	Engineering Subsystem Mass, kg	Science Instrument Mass, kg	Total Dry Mass, kg	Propellant Mass kg (1)	Max Earth Range (AU)	Max Downlink kb/s (receiver antenna size)	Total delta V, m/sec	Pointing, mrad (3 sigma)	Data Storage, Mb	Beginning of Life, Power, W
Mariner 4 '64	235	16	251	10	2.3	0.033 (26m)	60		5	700
Mariner 6 & 7 '69	355	58	413	10	2.5	0.033 (26m); 16.2 (64m)	59		23	830
Mariner 9 '71	438	68	506	491	2.5	16.2 (64m)	1650	25	180	830
Mariner 10 '74	396	78	474	29	1.7	117.6 (64m)	119		180	490
Viking 1 & 2 '75	825	74	898	1440	2.5	16.0 (64m)	1551	2.5	1120	1400
Voyager 1 & 2 '77	600	117	717	106	40+	115.2 @5 AU; 45 @10 AU (70m)	380	2.5	500	475
Magellan '89	899	132	1031	128	1.7	267 (70m)	2885	2.7	3600	810
Mars Observer '92	931	141	1072	1383	2.5	74 (34m)	2306	8.1	2100	900
Galileo '89	1051	105	1156	957	5.2	134 (70m)	1650	2.5	900	570
Mars Global Surveyor '97	582	77	660	381	2.5	85.3 (34m)	1290	8.1	3000	605
Cassini '97	1754	363	2117	3132	10	249 (70m)	2360	1	3600	800
Pathfinder, Mars Lander '96	740	9	749	85	2.5	11.06 (70m)	131	19	1024	270

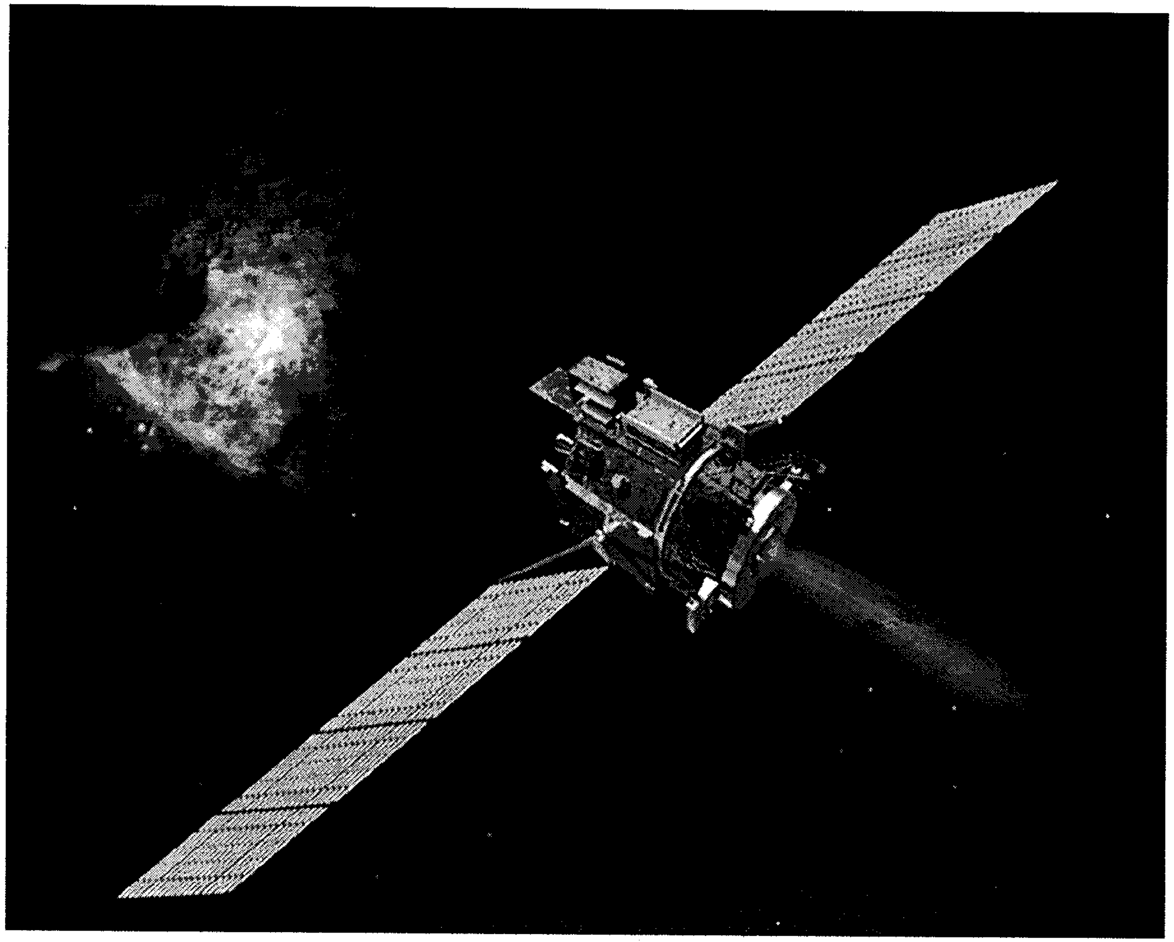

FIG. 15. Launched in 1998, Deep Space 1 has successfully tested twelve advanced technologies in space, including the first operational use of an ion engine, which serves as its main engine. Now on its extended mission, the spacecraft is set to fly by the comet Borrelly in late 2001. Deep Space 1's solar arrays continue to work flawlessly, powering all of the probe's systems, including its ion engine, which recently completed 365 days of operation in space.

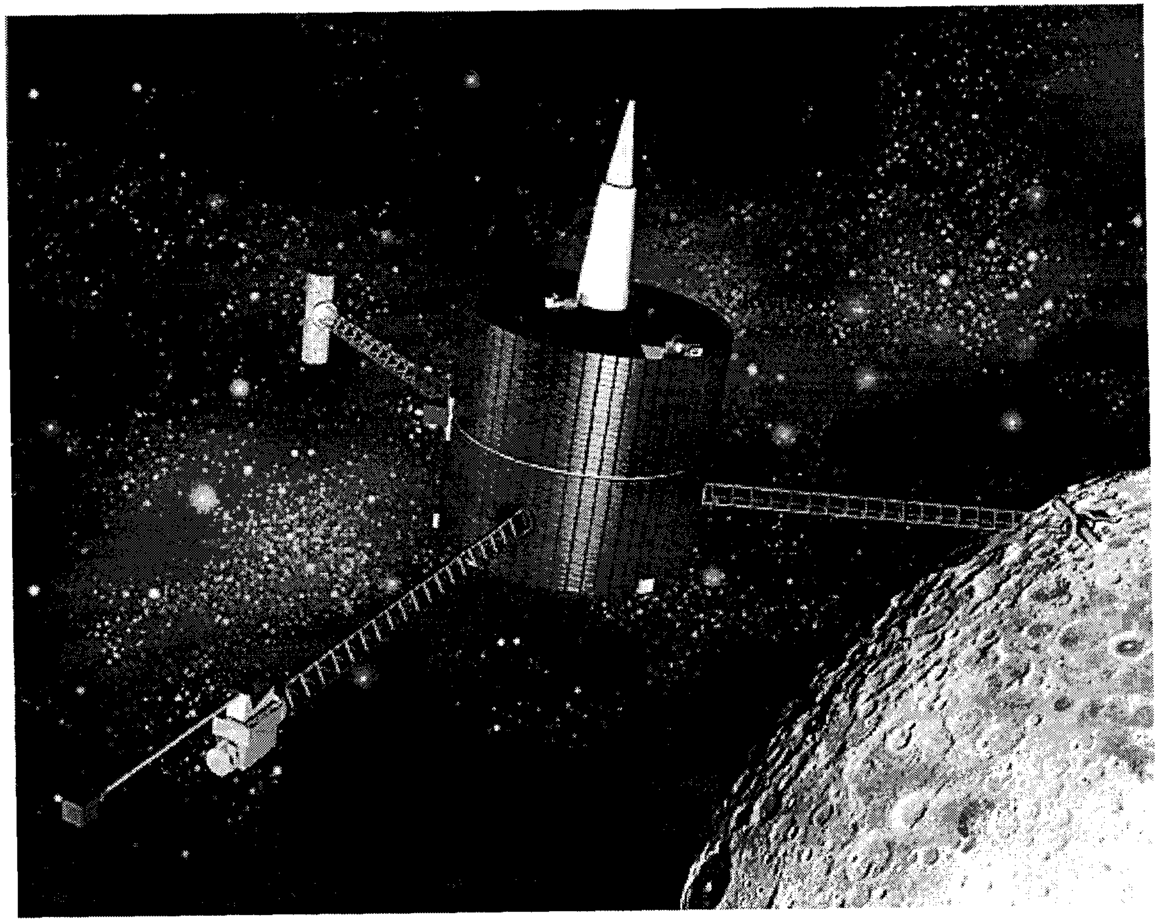

FIG. 14. Lunar Prospector's controlled crash into a crater near the south pole of the Moon in 1999 produced no observable signature of water, but from Prospector's data collected during the mission while in orbit, scientists estimate that up to six billion metric tons of water ice may be buried in craters near the Moon's south and north poles. Mission findings were also used to develop the first precise gravity map of the entire lunar surface.

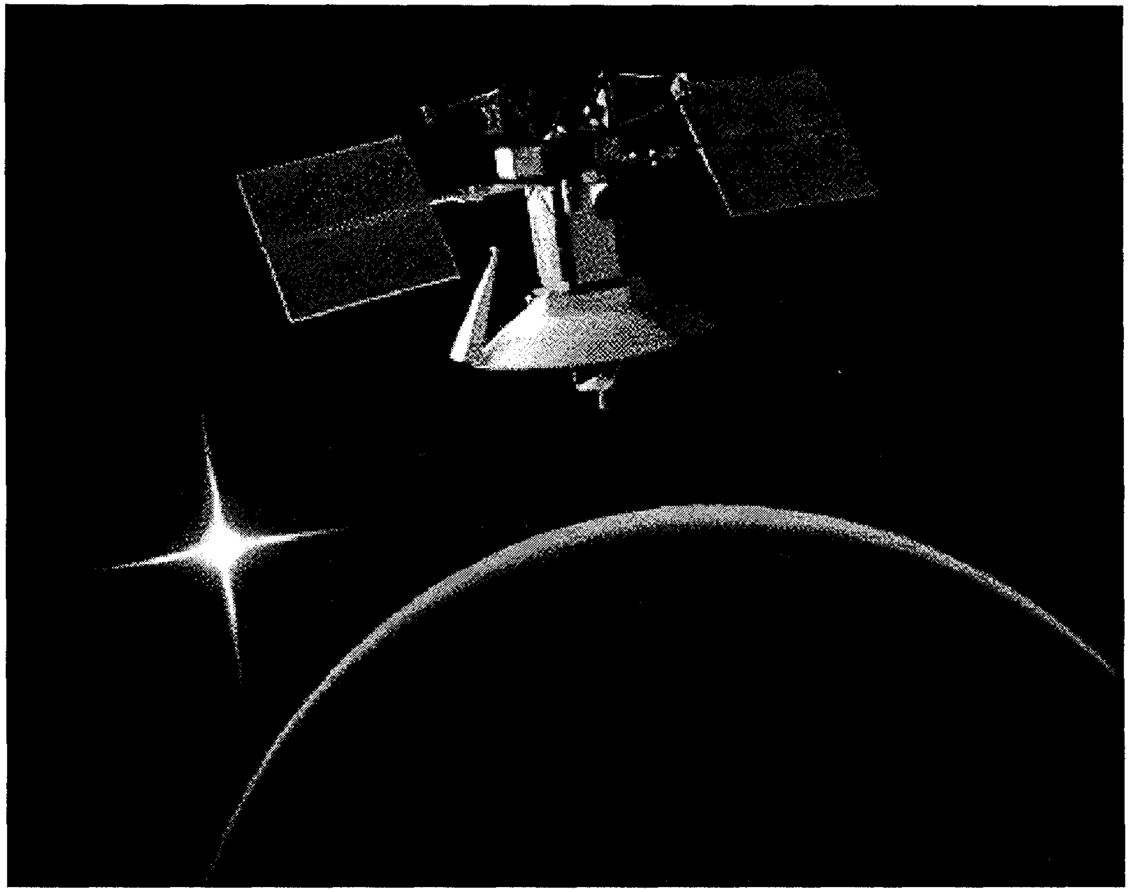

FIG. 13. The Magellan spacecraft was carried into Earth orbit by the Space Shuttle Atlantis and was propelled to Venus by a solid-fuel motor. Entering orbit in late 1990, Magellan pierced Venus' veil of swirling clouds, mapped its surface with its imaging radar, and dramatically improved upon the mapping resolution of orbiters the U. S. and the U.S.S.R. sent in the 1970s and early 1980s. Flight controllers tested a new maneuvering technique called aerobraking that uses a planet's atmosphere to slow a spacecraft. At mission end in 1994, Magellan's orbit was lowered a final time and it plunged to the planet's surface; contact was lost the following day.

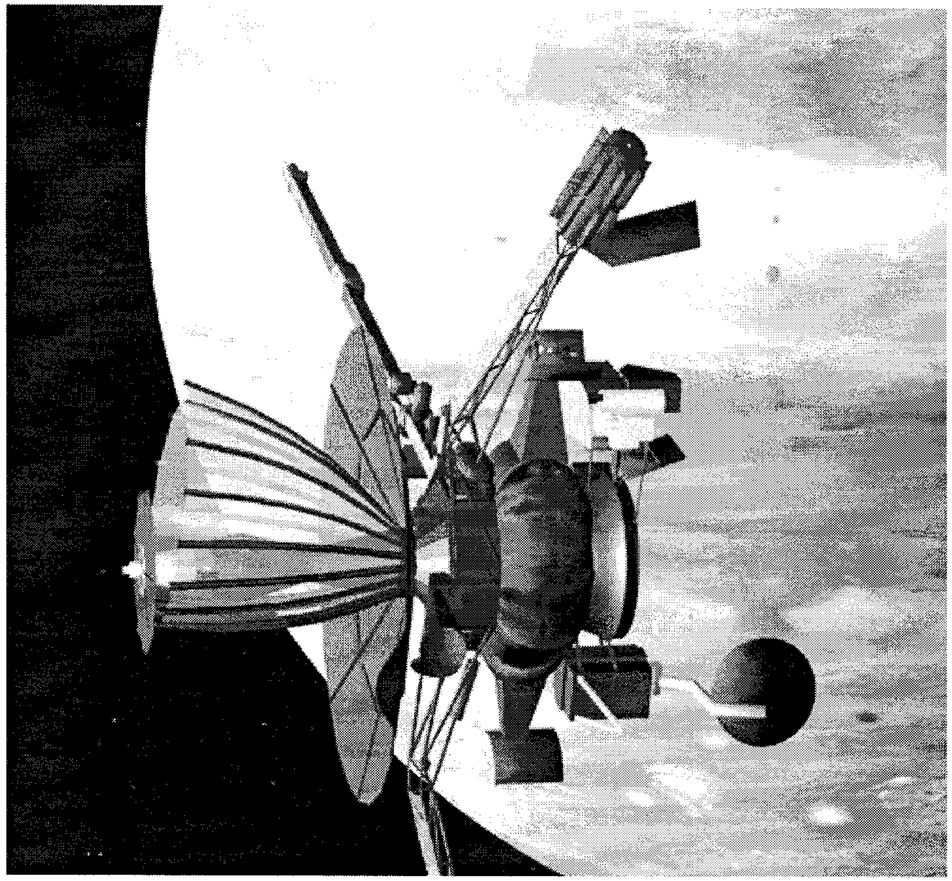

FIG. 12. Arriving at Jupiter in late 1995, the Galileo spacecraft entered orbit and dropped its instrumented probe into the giant planet's atmosphere. Since then it has made dozens of orbits around Jupiter and flown close to each of its four major moons. Galileo discovered that the cratered surface of Jupiter's moon Europa is mostly water ice, and there is strong evidence that it may be covering an ocean of water or slushy ice. Galileo also found indications that two other moons, Ganymede and Callisto, have layers of liquid saltwater as well. Half of the spacecraft contains pointable instruments such as cameras, and is held fixed in relation to space; the other half, containing instruments that measure magnetic fields and charged particles, slowly rotates in order to optimize the measurements. Other major science results include details of varied and extensive volcanic processes on the moon Io, measurements of conditions within Jupiter's atmosphere, and the discovery of a magnetic field generated by Ganymede. Despite heavy radiation doses, Galileo continues to return science in an extended-mission phase.

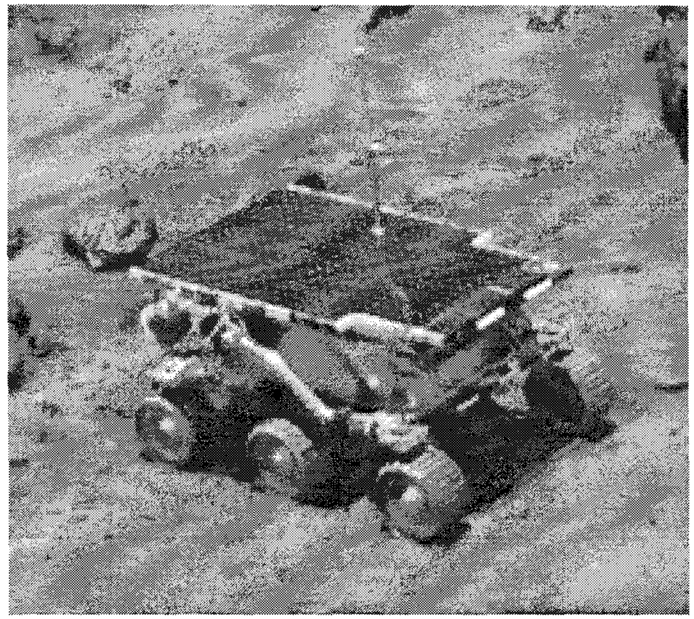

FIG. 11. Deployed on Mars' surface on 6 July 1997, Mars Pathfinder's Sojourner rover measures 280 mm high, 630 mm long, and 480 mm wide. Using rover and lander images, an Earth-based operator controlled the rover. But, an onboard, hazard-avoidance system allowed it some autonomous control as it explored the surface, so it would not always have to wait for commands from Earth due to the light-time delay of 10-15 minutes. 0.2 square meters of solar cells on the rover provided energy for several hours of operations per sol (1 Martian day = 24.6 Earth hours).

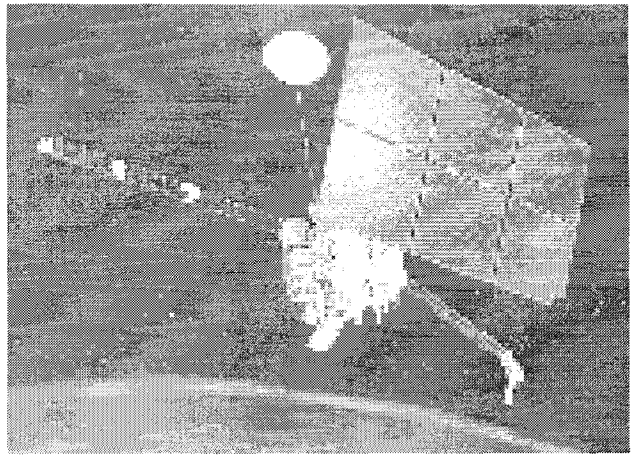

FIG. 10. Mars Observer's science instruments were designed to study Mars' geology, geophysics and climate. Unfortunately, contact was lost with the spacecraft shortly before orbital insertion in late 1993. The mission's science instruments are currently flying on two newer orbiters, Mars Global Surveyor and 2001 Mars Odyssey.

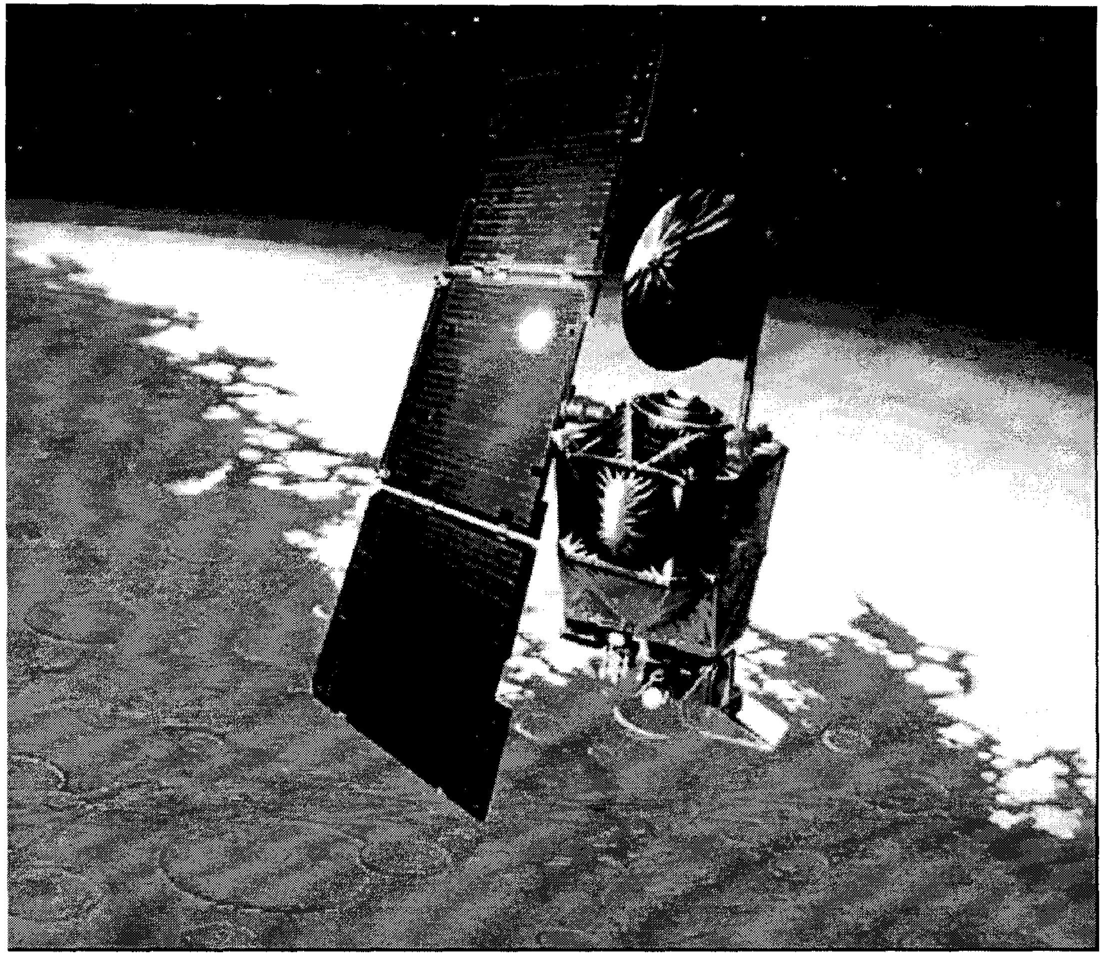

FIG. 9. Mars Climate Orbiter was designed to investigate the surface and atmosphere of Mars and function as a communications relay for Mars Polar Lander. The orbiter carried two science instruments: an atmospheric sounder, and a lightweight color imager combining wide- and medium-angle cameras. Mars Climate Orbiter was lost on arrival in late 1999. Engineers concluded that the spacecraft entered the planet's atmosphere too low and probably burned up.

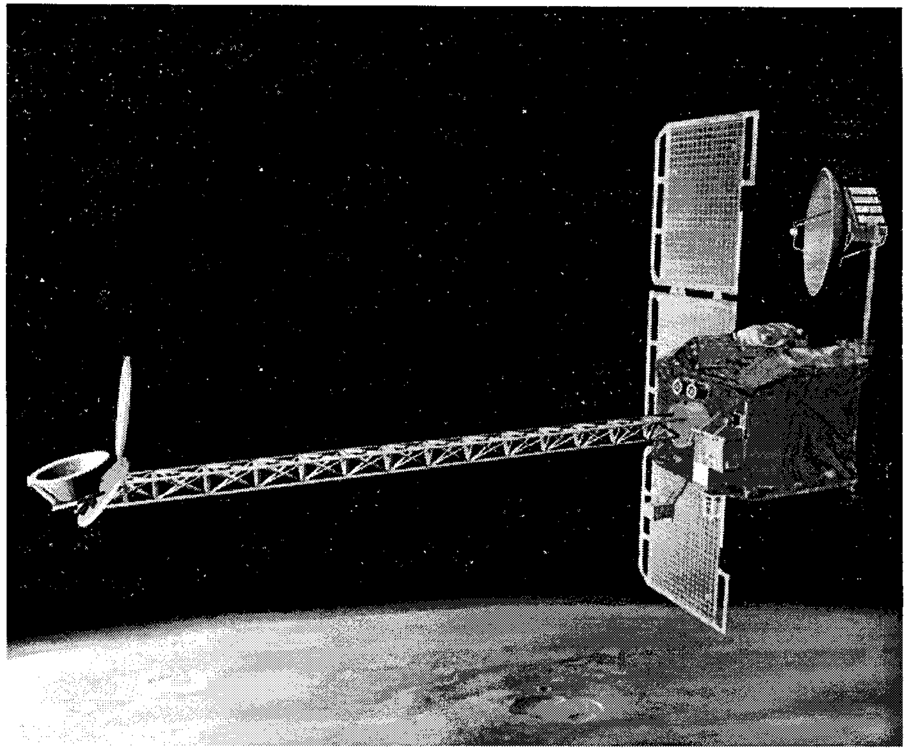

FIG. 8. With a mass of 758 kg, 2001 Mars Odyssey carries science instruments including a thermal-emission imaging system, a gamma-ray spectrometer, and a Mars' radiation-environment experiment. Due at Mars in late 2001, the Odyssey orbiter's mission is to determine the planet's surface composition, detect water and shallow, buried ice, as well as study the radiation environment. Mars' surface has long been thought to consist of a mixture of rock, soil and icy material, but the exact composition is largely unknown. Odyssey will help identify soil minerals and surface rocks, and study small-scale geologic processes as well as future landing-site characteristics. By measuring the amount of hydrogen in the entire planet's upper meter of soil, the spacecraft will uncover the amount of water available for future exploration, and more clues about Mars' climate history. The orbiter will also collect radiation data to help assess risks to future human explorers, and act as a communications relay for future Mars' landers.

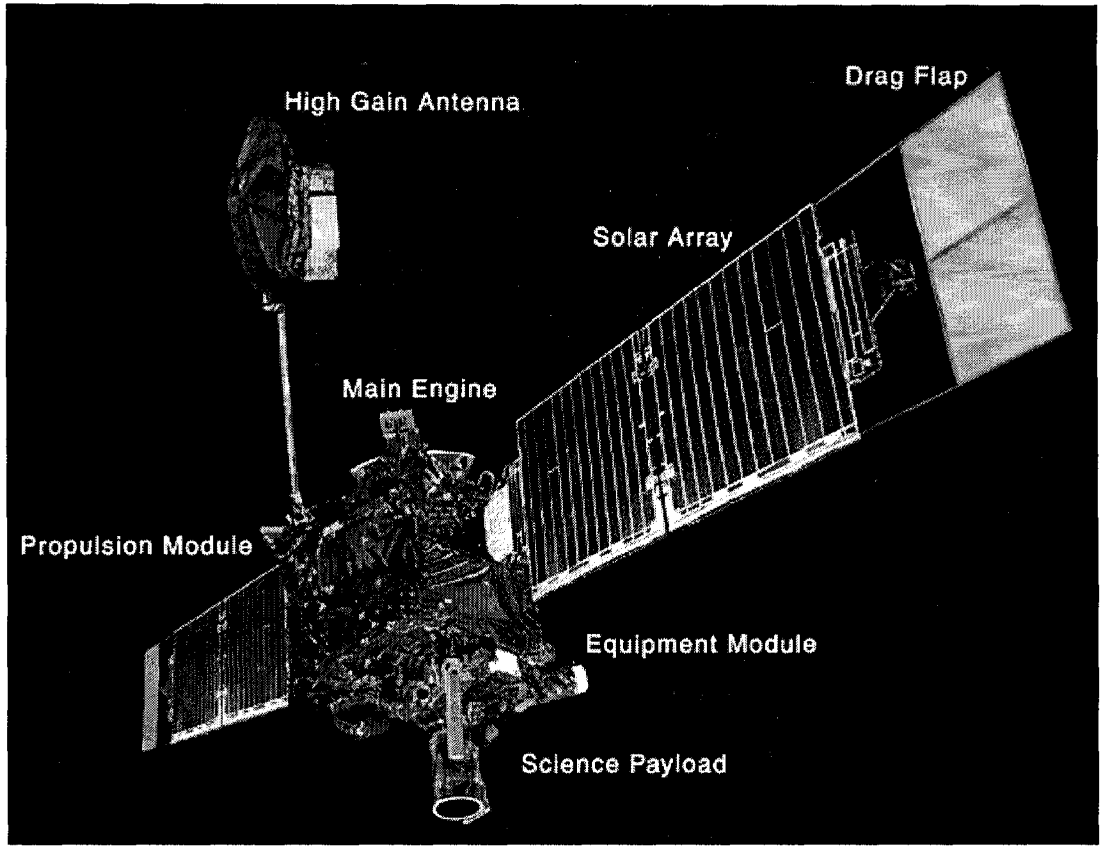

FIG. 7. Entering Mars' orbit in late 1997, Mars Global Surveyor was the first successful mission to the red planet in two decades. MGS science instruments include: a high-resolution camera, a thermal emission spectrometer, a laser altimeter, a magnetometer/electron reflectometer, an ultra-stable oscillator, and radio-relay system. Beginning its prime-mapping mission in early 1999, MGS has studied the entire Martian surface, atmosphere and interior from a low-altitude, nearly polar orbit over one Martian year (almost two Earth years). Having completed its primary mission in early 2001, it continues in an extended mission phase. MGS has returned more data about the red planet than all other Mars' missions combined.

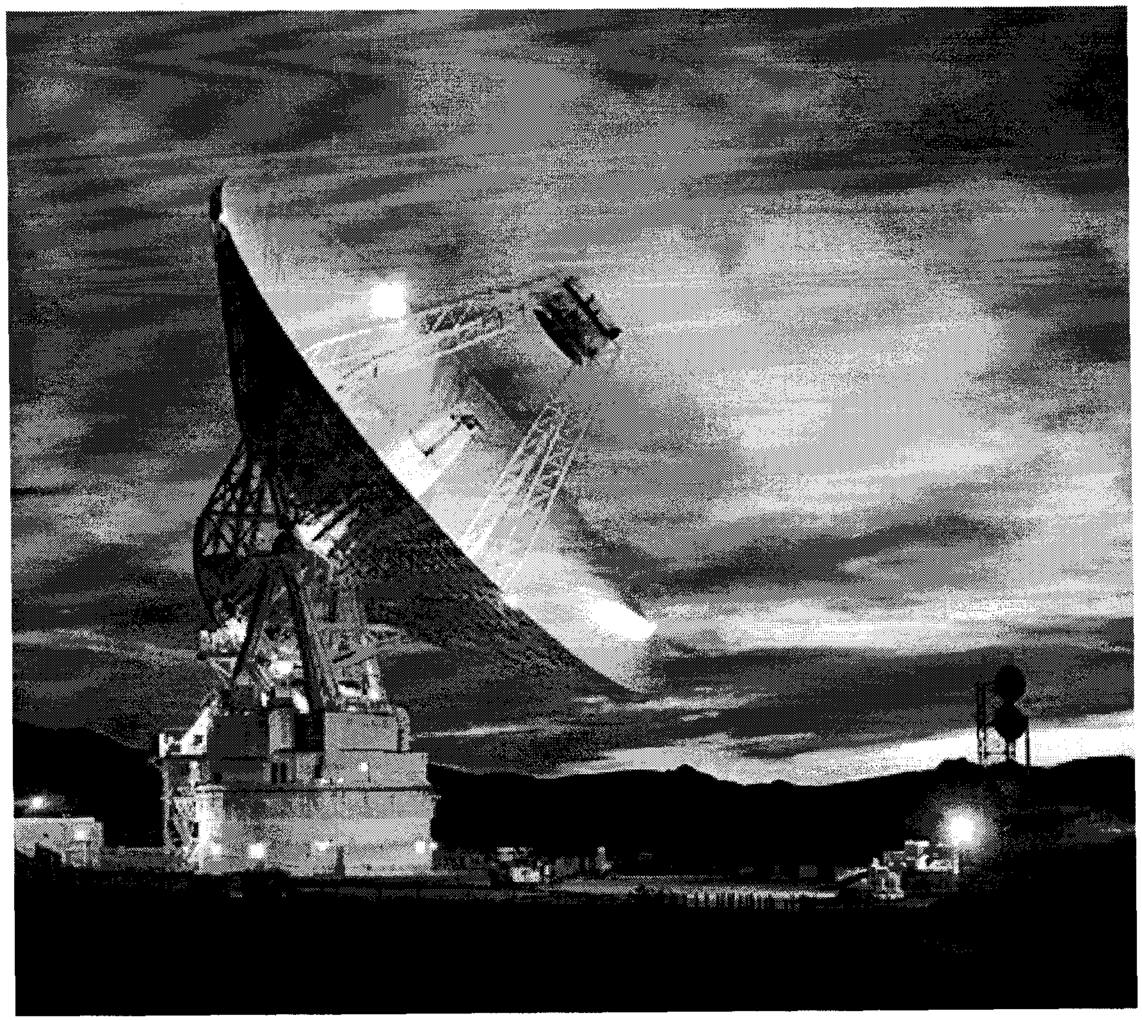

FIG. 6. The Deep Space Network (DSN) is an international network of antennas that supports interplanetary spacecraft missions, and radio and radar astronomy observations that explore the solar system and the universe. Via its vital two-way communications link, the network guides and controls interplanetary explorers, and brings back the images and new science data that they collect. All DSN antennas are steerable, high-gain, parabolic reflector antennas.

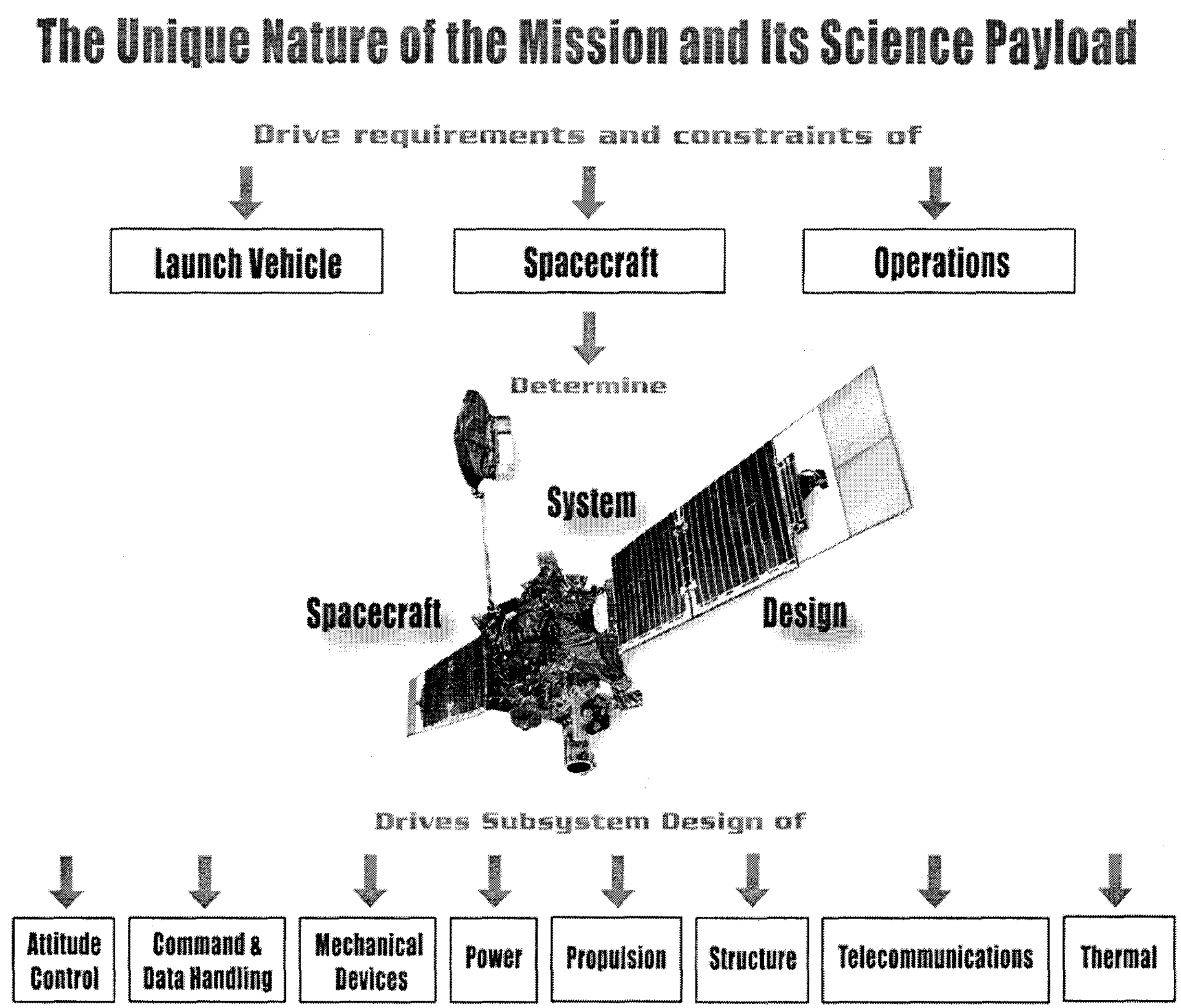

Fig. 5. Planetary-spacecraft design flow.

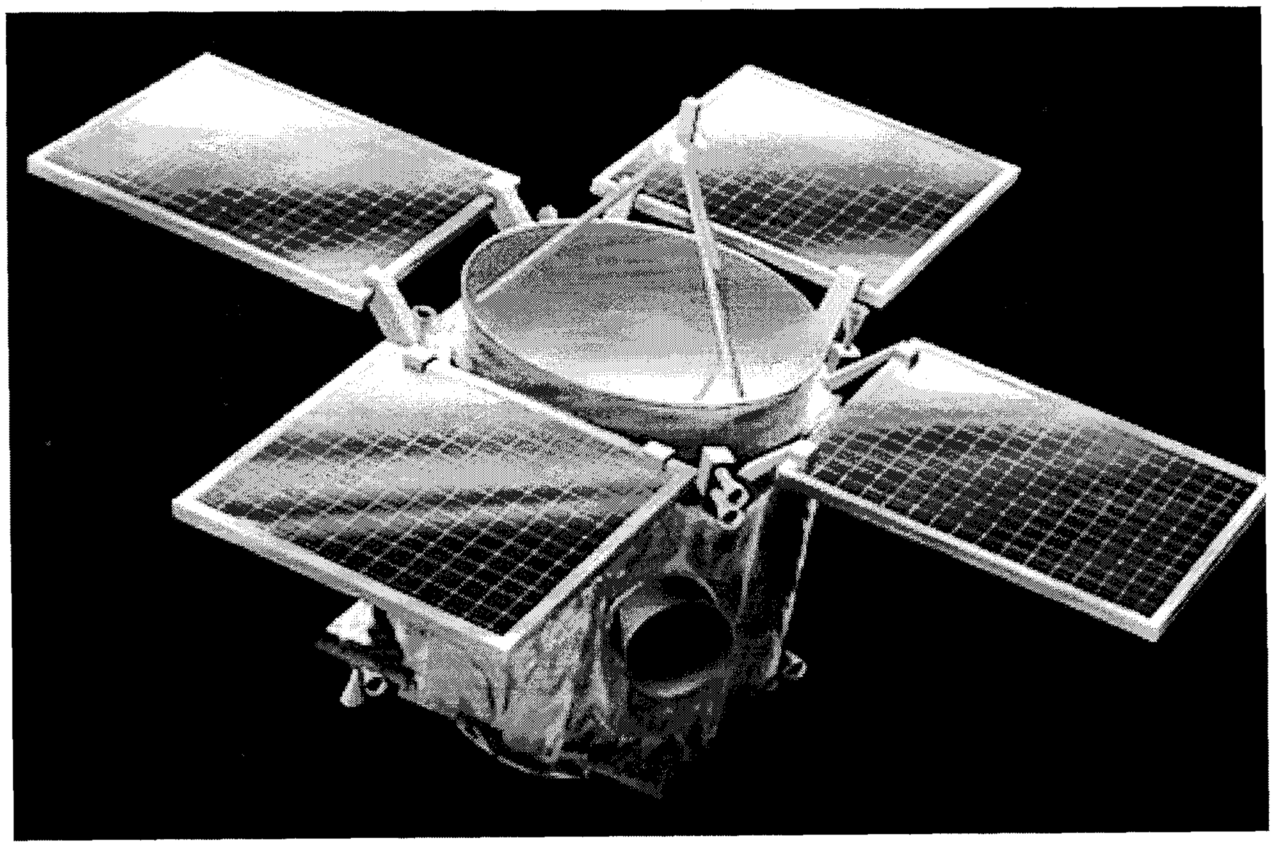

FIG. 4. In 1996, NEAR-Shoemaker was the first Discovery Program spacecraft to be launched, and four years later in February, 2001 became the first ever to orbit and land on an asteroid. Using six highly-specialized instruments to gather data about its primary target, asteroid 433 Eros, NEAR is beginning to answer many fundamental questions about the nature and origin of asteroids and comets. The spacecraft snapped 69 detailed pictures during the final three miles (five km) of its descent, the highest resolution images ever of an asteroid, showing features as small as one centimeter across.

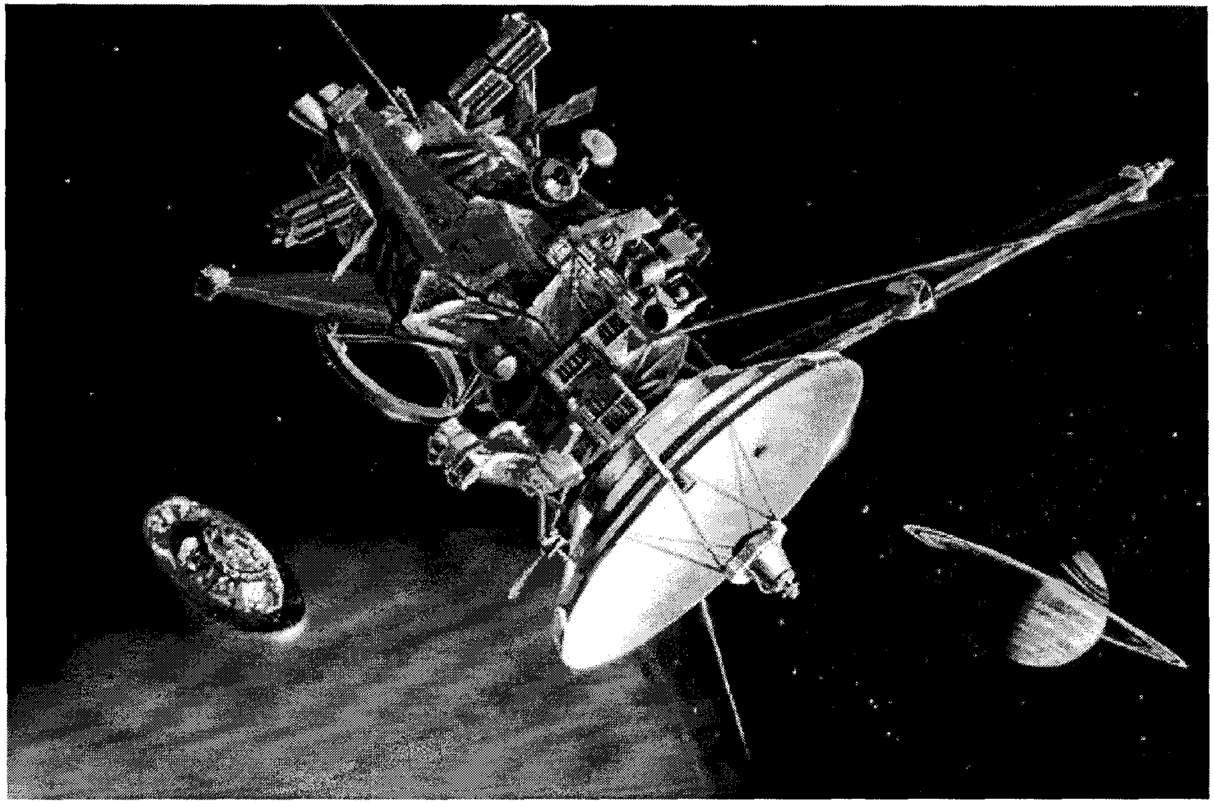

FIG. 3. A joint endeavor of NASA, the European Space Agency (ESA) and the Italian Space Agency (ASI), Cassini is a sophisticated robotic spacecraft that will orbit the ringed planet and study the Saturn system in detail over a four-year period. Launched in late 1997 on a Titan 4 rocket, Cassini has flown past Venus and Jupiter, and twice past Earth, on its way to Saturn. Cassini will enter Saturn orbit, and the Huygens probe will descend to the surface of Titan in late 2004. Cassini is the most ambitious planetary-exploration mission ever mounted.

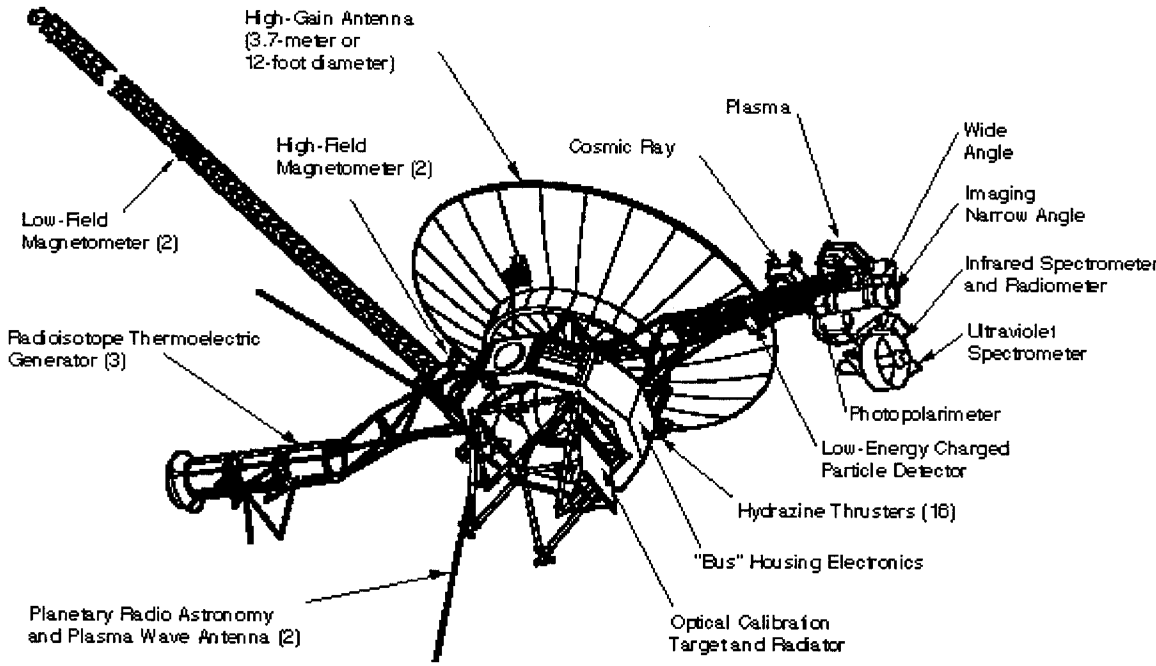

FIG. 2. The twin spacecraft Voyager 1 and 2 flew by and observed Jupiter and Saturn; Voyager 2 went on to visit Uranus and Neptune. In 1998, Voyager 1 became the most distant human-made object in space.

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Ross Jones Biography

Ross Jones has a B.S. degree from Purdue University, and an M.S. degree from Massachusetts Institute of Technology in Aeronautical and Astronautical Engineering.

He has been with the Jet Propulsion Laboratory for 23 years.

Currently, Mr. Jones is the project system engineer on the Mars Reconnaissance Orbiter project at JPL. Before this assignment, he was project manager for the MUSES CN rover project, and supervisor of the Advanced Flight Systems Group in the Mission and System Architecture Section at JPL.

Mr. Jones has also worked in the Mission Design Section and Power Systems Sections at JPL. He was also instrumental in the creation of the concept of micro-spacecraft for planetary missions in 1988.

Mr. Jones has authored 20 papers on various aspects of advanced mission and technology concepts for planetary exploration.

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