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Mariner Mark II and the Exploration of the Solar System

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As planetary spacecraft technology evolved from the relatively simple Mariner flybys of Venus and Mars to the planned Galileo mission to Jupiter, the emphasis has always been on improved performance. Each mission has returned greater amounts of more sophisticated data than its predecessors. Today, because of severe economic constraints, the outlook is different. The Solar System Exploration Committee (SSEC) of the National Aeronautics and Space Administration (NASA) has been developing a strategy for future planetary research based on a lower cost per mission rather than higher performance.

Summary. Mariner Mark II is a concept for the next generation of deep-space missions. The project would provide limited, focused sets of Voyager- and Galileo-quality planetary observations at a fraction of the cost of the Voyager and Galileo projects. This article discusses Mariner Mark II's cost goals, scientific objectives, and mission requirements. Strategies for limiting costs include the use of a reconfigurable spacecraft, a multimission ground-support system, and selected new technologies.

The SSEC is considering both near-Earth and deep-space missions. Many of the near-Earth missions (to the moon, Venus, Mars, and Earth-approaching asteroids) may be accomplished at relatively low cost with the present generation of Earth-orbiting spacecraft. Several aerospace companies are analyzing methods for adapting spacecraft such as Tiros, Atmospheric Explorer, Fltsatcom (fleet satellite communications), and GOES (geostationary orbital earth satellites) to study Martian geochemistry, climate, and atmosphere, to map the geochemical properties of the moon, or to explore a near-Earth asteroid.

Deep-space missions to comets, main-belt asteroids, and the outer planets require specially designed power, telecommunications, and thermal control systems that operate over a large range of distances from Earth. Under the direction of NASA and SSEC, the Jet Propulsion Laboratory is studying the development of a workhorse called Mariner Mark II for the next generation of deep-space planetary missions. Mariner Mark II is being designed to perform limited sets of Voyager- or Galileo-quality measurements in deep space or to deliver Galileo-type atmospheric probes to the outer planets at a fraction of the cost per mission of the Voyager and Galileo projects.

Tens of thousands of striking pictures of the Jupiter and Saturn systems were sent back by Voyager (*1*). These pictures were obtained by a black and white television camera with a resolution of 800 by 800 picture elements (allowing finer detail than possible with the 520 lines of an ordinary television). Color photography and spectral information were obtained by sequential use of a set of different filters. For Galileo, the Vidicon television tube used on Voyager will be replaced by solid-state detectors called charge-coupled devices (CCD's) to achieve wider spectral response, greater photometric accuracy, and increased sensitivity. The term Voyager- or Galileo-quality also implies the following: (i) the capability to map certain physical properties and the chemical composition of individual features on the surfaces of solid bodies; (ii) the capability to determine the structure and dynamics of planetary atmospheres together with the abundances of many specific atoms and molecules by remote sensing at ultraviolet, visible, and infrared wavelengths; (iii) the capability to send an instrumented probe into a planetary atmosphere to sense the frequency and intensity of lightning bursts and to directly sample pressure and temperature structure, composition (both elemental and isotopic), and the size and shape of aerosols; (iv) the capability to measure the composition and distribution of energetic charged particles and low-energy plasmas in planetary ionospheres and magnetospheres, together with the magnetic field and plasma waves that interact with the charged particles; and (v) the capability to determine the distribution and some of the physical and chemical properties of dust grains by observing the details of how they absorb and reflect sunlight and by direct measurements of a few individual grains.

Mariner Mark II starts with these existing capabilities and uses new technology principally to reduce mission costs rather than to improve spacecraft performance. The spacecraft would be reconfigurable at low cost to meet the different requirements of different missions, while a multimission ground system would be able to support any of the spacecraft without reconfiguration.

The cost history of U.S. planetary and interplanetary projects is shown in Fig. 1 in terms of both dollars spent and an equivalent 1982 cost that accounts for inflation. Twin spacecraft, such as Voyagers 1 and 2, are counted as a single project. A much lower than average cost characterizes missions that were based on the designs of earlier missions. These

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include Mariners 1 and 2, derived from earlier Ranger spacecraft; Mariner 5, derived from Mariners 3 and 4; and Mariners 8, 9, and 10, derived from Mariners 6 and 7. The goal of the Mariner Mark II project is to develop the capability for a series of planetary missions in the 1990's with a 1982-equivalent cost between $150 million and $300 million per mission. For a sequence of four or five missions in 10 years the average expenditure per year is planned to be limited to approximately $100 million. The data in Fig. 1 suggest that these goals are probably attainable if a high level of inheritance can be achieved across missions.

Ironically, one reality that brings the Mariner Mark II goals within reach is the present time gap in funding planetary exploration. The Galileo project, which was approved and started in 1977, is the only planetary mission under development in the United States. The gap between the start of Galileo and the start of the next deep-space project is being used to examine the requirements of this next generation and to determine the most cost-effective way of meeting them.

The study of comets is one of the highest priorities of future planetary research (*2*). Comets are the only obtainable source of the primitive material from which the solar system evolved. They are believed to contain a record of the physical and chemical conditions of the interstellar medium and the primordial solar nebula. Furthermore, comets may have contributed appreciable amounts of volatile material to the present atmospheres of the terrestrial planets (*3*); it has also been suggested that cometary material was important to the evolution of life on Earth (*4*).

The 1986 European, Soviet, and Japanese flybys of Halley's comet will address many important questions about the composition of the gas and dust that form the cometary halo and tails visible from Earth. The missions are expected to verify Whipple's (*5*) hypothesis that cometary nuclei are small (diameter, 0.1 to 100 kilometers) "dirty snowballs" that vaporize and become very active when they come close to the sun.

A thorough investigation of a comet requires a much longer period of observation than that provided by a flyby mission. A rendezvous mission is required so that the comet can be watched for a period of months as it approaches and retreats from the sun. With very small propulsion maneuvers, a spacecraft in rendezvous with a comet can move around the nucleus and view it from different distances and directions. The physical and chemical nature of the nucleus can be determined with Galileo-quality imaging and infrared mapping systems as well as with x-ray or gamma-ray spectrometers. Direct measurements can also be made of the gas and dust in the comet's atmosphere.

The choice of targets for a comet rendezvous is limited by available and planned launch vehicles to short-period comets in low-inclination orbits. Comets Honda-Mrkos-Pajdusakova and Tempel 2 are the two best candidates for the 1990's.

While observations with a rendezvous spacecraft can enormously increase our knowledge of comets, the ultimate step would be to collect and return a portion of a comet's nucleus for detailed analyses in sophisticated ground-based laboratories. The propulsion capability required to carry out such an ambitious task is not available; it is possible, however, to sweep up cometary gas and dust with a spacecraft that passes through a comet's atmosphere at high velocity and to return that sample to Earth for analysis. The spacecraft would necessarily move through the comet at such high speed that information about the physical and chemical states of the dust and gas would be lost because of vaporization and plasmatization caused by the impact. But elemental and isotopic analyses of the collision debris would provide new information on the generic relation of the comet to other solar system bodies and to interstellar matter. A high degree of synergism can be gained by studying the same comet with simultaneous rendezvous and sample-return missions.

Like comets, asteroids are relevant to a wide variety of questions about the origin and evolution of the solar system. Since asteroids are relatively small bodies, it is thought that radiogenic heating and other endogenic processes have had much less effect on them than on larger bodies such as the Earth and moon. An asteroid's structure and morphology and some features of its mineralogy and elemental composition should indicate its environment and state during and shortly after its creation. Earth-based observations indicate that there are many different types of asteroids. For spacecraft missions there are two sets of objects to be considered: main-belt asteroids between the orbits of Mars and Jupiter and Earth-approaching asteroids on temporary, unstable orbits with typical lifetimes of a few tens of millions of years. The source of Earth-approaching asteroids is not known; some or all of them may be exhausted comets. There is also an apparent systematic variation of composition with position in the asteroid

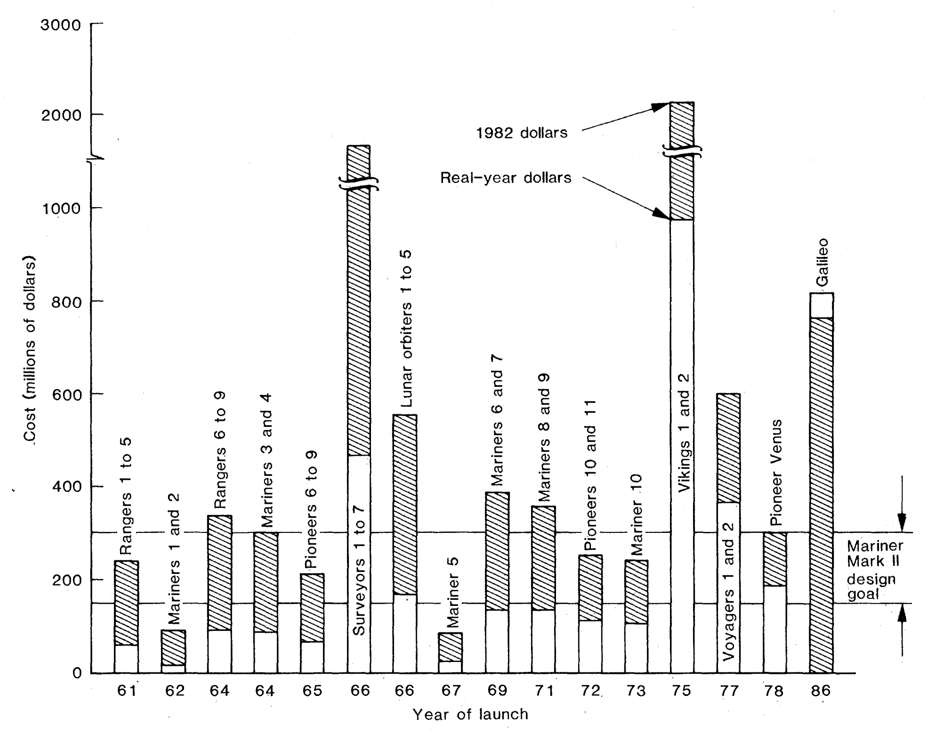

Fig. 1. Deep-space mission costs. The figures reflect current NASA bookkeeping practice in that they include all costs of building and operating the spacecraft and analyzing the returned data, but not the cost of either the launch vehicle or the operation of the deep-space data acquisition facilities. Data for Pioneers 10 and 11, Pioneer Venus, and Voyager are through the end of fiscal year 1981.

belt, which is probably a relic of radial gradients in the condensing solar nebula. The diversity of asteroids requires that more than one type be studied at close range.

The Mariner Mark II study addresses the possibility of performing a rendezvous with one or possibly two main-belt asteroids and flying by several others, all with a single spacecraft. Main-belt asteroid rendezvous missions could be achieved with Galileo-era launch vehicles by designing a trajectory that takes the spacecraft close enough to Mars to obtain a gravitational boost in orbital energy from that planet. Additional energy could be gained by proper timing of a rocket firing during the Mars encounter. Such a maneuver would allow the spacecraft to obtain an asteroid-like orbit about the sun. Once the spacecraft reached the asteroid belt there would be a very large number of target bodies to choose from.

Future planetary exploration will also focus on the outer planets. Again, the emphasis will be on learning more about the origin and evolution of the solar system. Systematic differences between Jupiter, Saturn, Uranus, and Neptune reflect radial variations in the physical and chemical properties of the primordial solar nebula. The outer planets have a wide variety of satellite and ring systems; understanding the dynamics of these systems is a prerequisite to understanding the agglomeration and accretion of the planets and their satellites. Other than the Earth, Saturn's moon Titan is the only solar system body with a nitrogen-rich atmosphere. Titan has been likened to the Earth early in its development. Large amounts of methane are also present, which raises the possibility of organic chemical reactions, possibly similar to those on the prebiotic Earth. It is possible that methane is near saturation in Titan's lower atmosphere and that liquid methane is present on the surface.

The Pioneer and Voyager missions provided an initial reconnaissance of Saturn and its rings and satellites, and Voyager is expected to do the same at Uranus in 1986. To achieve the next level of understanding, Mariner Mark II could deliver entry probes or provide a Saturn orbiter. Because Titan's atmosphere is opaque at visible wavelengths, Voyager could learn only a little about the composition and structure of its atmosphere and nothing about the physical nature of its surface. New data could be obtained by sending an instrumented probe into Titan's atmosphere and by observing Titan at infrared and radio wavelengths. Radar and infrared mapping could be carried out from the spacecraft used to deliver the atmospheric probe and to relay its data to Earth. More complete mapping could be conducted from a spacecraft in orbit around Saturn.

A Saturn orbiter would, of course, have other objectives in addition to studying Titan, and a variety of different Saturn orbits can be obtained by repeated close flybys of Titan. The 3-year scenario shown in Fig. 2 features 22 encounters with Titan plus close (< 2500 km) encounters of the satellites Dione, Rhea, Hyperion, and Iapetus. The key element provided by a Saturn orbiter is the ability to study satellite surfaces and Saturn's atmosphere as well as ring and magnetospheric phenomena over an extended period of time and at a variety of geometries and conditions.

As with Titan, new data about the atmospheres of each of the outer planets can be obtained with entry probes. Instruments like those carried on the Galileo Jupiter probe would be able to measure the molecular and isotopic compositions of the atmospheres of Saturn, Uranus, and Neptune as functions of depth down to pressure levels of 10 to 20 bars.

The Mariner Mark II is principally designed to study minor bodies and the outer solar system. But its capabilities could be applied to study the terrestrial planets as well. The option that has been studied in greatest detail is a Mars orbiter suited for geochemical and climatic studies. The reason for studying Mars is not so much to increase our knowledge of how the solar system evolved but rather to learn more about how it is evolving and, in particular, to understand what may be in store for the Earth. An understanding of past and present processes on Mars requires mapping of the chemical and mineralogical characteristics of the surface and determining the sources, sinks, abundances, and circulations of volatiles and dust in the atmosphere.

Mission Characteristics and Requirements

The space shuttle would be used as a launching platform for all the Mariner Mark II missions. The boost out of low-Earth orbit would be provided by the Air Force two-stage Inertial Upper Stage (IUS) or a higher energy Centaur rocket using liquid hydrogen and oxygen as fuels (Table 1). Funds for the development of a shuttle-compatible Centaur were approved in July. Some proposed missions require still another stage of propulsion, which could be provided by a Star-48 solid rocket motor after the IUS or Centaur has burned out and been jettisoned.

Most of the candidate missions have substantial requirements for postlaunch propulsion for orbit insertion, for matching the velocity vector of a rendezvous target, or for interplanetary maneuvers required to reach the target. Many of the candidate missions are also of long duration, ranging up to 11 years. This fact has a significant impact on the reliability

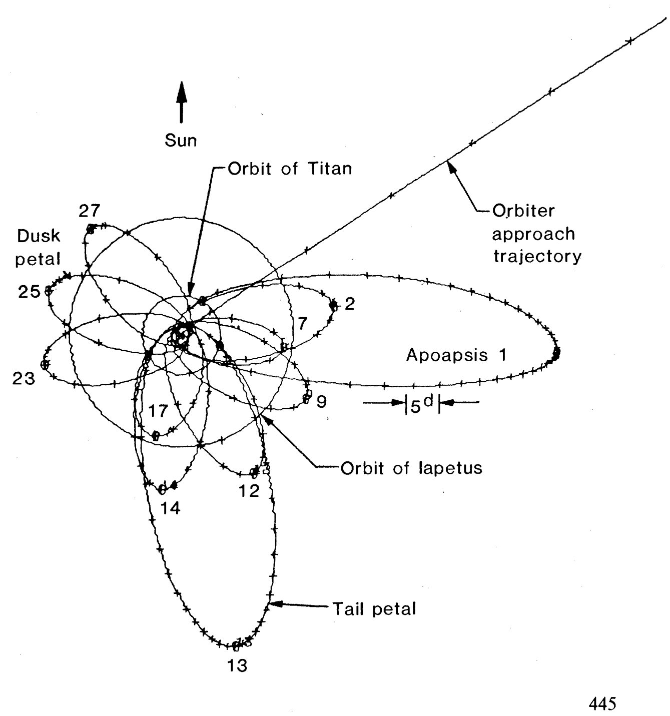

Fig. 2. Example of one possible 3-year tour of the Saturn system (6). For clarity, only ten of the 26 orbital loops have been drawn.

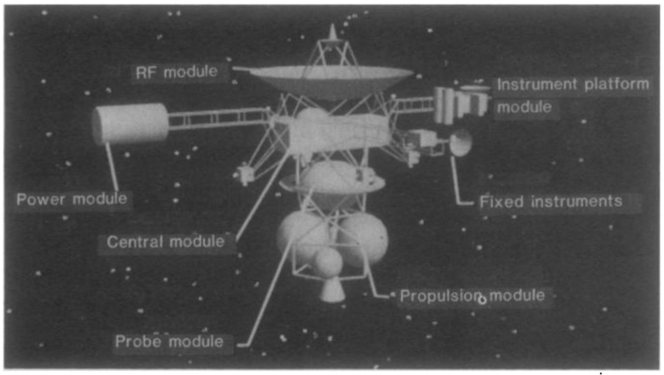

Fig. 3. Mariner Mark II modular spacecraft concept; *RF*, radio frequency.

required of the spacecraft and on the level of redundancy in the design.

Many of the missions will require precise navigation. The Titan mission must rely on optical navigation for acceptably accurate delivery of its atmospheric probe. The ephemerides of the comet and asteroid targets are even less well known because of the relative scarcity of observations. Furthermore, as gas escapes from the warmer side of a comet, conservation of momentum results in an acceleration of the comet body in the opposite direction. The comet's orbit can be substantially altered by such jet action. Optical navigation requires imaging of the comet or asteroid against a background of stars of magnitude 9 or 10. This requirement can be easily met with the Galileo CCD camera sensor on a three-axis–stabilized platform.

Voyager- or Galileo-quality imaging will also be of highest scientific priority for the comet and asteroid rendezvous and the Saturn orbiter missions. Remote-sensing instruments also benefit greatly if the spacecraft is able to keep them trained on the target. Measurements that require long integration times are made possible through the use of a platform with active pointing control. Over 80 percent of the surface of Titan can be mapped with a radar antenna mounted on a movable scan platform such that one hemisphere is viewed on approach and the other as the spacecraft leaves Titan. Thus, navigation and remote sensing both call for a stabilized rather than a spinning spacecraft.

The imaging systems, multispectral mapping instruments, and radar for the Titan mission will all produce large amounts of data. Model profiles suggest that, even with the data compression techniques now coming into use, telecommunication rates will be on the order of 10,000 to 30,000 bits per second. The data links must be maintained over distances as great as 10.5 astronomical units (AU) for Saturn. The distances to Uranus and Neptune are even greater, but the smaller amount of data acquired by flyby and probe missions can be stored and then transmitted at a lower rate.

Other requirements of the Mariner Mark II spacecraft include the following: (i) it must operate at distances from the sun ranging from 1 to 30 AU, if a Neptune mission is included in the set; (ii) it must be capable of carrying and releasing an atmospheric probe or a capsule to return material to Earth; (iii) for missions with high-resolution imaging, it must have a pointing accuracy of about 2 milliradians; and (iv) it must support and be compatible with the scientific instruments to be flown.

The basic requirements of the Mariner Mark II spacecraft are summarized in Table 2. Some of these requirements would have to be extended, at additional cost, to carry out certain missions. These extensions include an on-board propulsion capability between 3 and 4 km/sec for some multiple main-belt asteroid tours, longer durations and larger distances for the Uranus and Neptune missions, and a closer approach (0.34 AU) to the sun if Encke were chosen as the target for a comet rendezvous mission.

Implementation

How is it possible to meet the requirements listed in Table 2 and the Mariner Mark II cost goals at the same time? The strategy, which is based on the assumption that Mariner Mark II will be used for a series of four or five missions over a 10-year period, has four components: (i) objectives and operations must be kept as simple as possible; (ii) the system must be easily reconfigured from one mission to the next; (iii) requirements must be set to provide more conservative design margins than in the past; and (iv) new technology should be used to reduce costs rather than to achieve performance beyond the minimum mission needs.

Simplicity. One way to keep the missions simple is to restrict the scientific objectives of each mission. Figure 1 shows that Viking and Galileo are two of the more expensive recent projects. Both missions have diverse rather than

Table 1. Summary of candidate Mariner Mark II missions.

Mission	Launch opportunities	Launch mode*	Mission duration (years)	Time spent at target	Post-launch ΔV (km/sec)
Comet rendezvous	1989, 1990,† 1991, 1992, 1994, 1995, 1996	Centaur	5.5	6 months	2.2 to 2.9
Comet sample return	1989, 1990, 1992, 1994, 1999	IUS	2 to 3	1 day	0.2 to 1
Main-belt asteroid flybys and rendezvous	Every 26 months	IUS, S48, and MGA or Centaur and MGA	2 to 7	6 months	3 to 4
Saturn orbiter	Every year (1998†)	Centaur and JGA	7 to 11	≤ 3 years	2.0 to 2.3
Titan or Saturn flyby and probe	Every year	Centaur and S48	3.5	1 day	0.2
Uranus flyby and probe	1992, 1994†	Centaur, S48, and JGA	5.5 to 8‡	1 day	0.2
Neptune flyby and probe	1992, 1994†	Centaur, S48, and JGA	8 to 10‡	1 day	0.2
Mars orbiter	Every 26 months	IUS	2.8 to 3.2	2.2 years	2.2 to 2.7

*The spacecraft would all be launched from the space shuttle by either a two-stage IUS propulsion system or by the higher performance Centaur. A notation of S48 indicates that an additional stage of propulsion equivalent to a Star-48 solid rocket motor is also required. Missions in which momentum is gained by flying by Mars or Jupiter are indicated by MGA or JGA, respectively. †Best opportunity. ‡The longer flight times would be required to avoid a close flyby of Jupiter, which requires special radiation hardening of spacecraft.

focused objectives. The Viking project had two orbiters for global mapping plus two landers that probed the atmosphere and then made detailed observations of the two landing sites. The Galileo project includes an atmospheric probe and an orbiter. The orbiter, in turn, has a three-axis–stabilized section to optimize remote sensing of Jupiter and its moons and a spinning section to optimize magnetospheric measurements. For Mariner Mark II, a Saturn probe, Titan probe, and Saturn orbiter would be three separate, focused missions. Furthermore, the Saturn orbiter would not have a spinning section. Adequate magnetospheric particle measurements could still be made with sets of wide-angle sensors. The disadvantage of a fixed orientation for magnetospheric measurements is generally outweighed by its advantage for remote sensing.

The ground-support system must also be as simple and as inexpensive as possible. Two keys to simplification of the ground system are automation and autonomy of the spacecraft—which, of course, increase the spacecraft's cost. The Mariner Mark II missions are generally of such long duration that the net payoff for on-board automation would be high. The spacecraft must be able to care for itself for many days without commands from the ground. During the long cruise toward the target, a radio signal would continuously indicate the state of health of the spacecraft. This signal would be monitored once or twice a week and an alarm system could be automatically activated if anything were amiss.

Once at the target, the sequencing of spacecraft operations must be as simple as possible, with a minimum number of modes or states of activity. With its large number of satellite encounters, the Saturn orbiter tour (Fig. 2) would be especially vulnerable to an escalation of costs associated with spacecraft and instrument sequencing. The inclusion of an automatic target tracker and "smart," self-adjusting instruments might be cost-effective for such a mission.

Each instrument must also operate as independently as possible. Power and data handling margins would be sufficiently large to allow an instrument to change its mode of operation, either automatically or by ground command, without prior coordination, scheduling, and simulation of the effect of the change on the spacecraft and the other instruments and without verification of proper receipt of commands.

Reconfigurability. A basic requirement of the Mariner Mark II concept is that the spacecraft be reconfigurable at low cost from one mission to the next. A high degree of inheritance from mission to mission must be planned from the start. A modular spacecraft configuration is being developed to satisfy this requirement over the range of missions listed in Table 1 (Fig. 3). The baseline attitude control mode is a three-axis, celestially fixed attitude with the Earth and a bright star as references. A central module houses all of the spacecraft electronics and electromechanical and electrochemical assemblies that do not require external mounting.

Table 2. Mariner Mark II spacecraft requirements.

Requirement	Possible extension
Shuttle IUS or Centaur launch	
Postlaunch propulsion, ≤ 3 km/sec	4 km/sec
Mission duration, ≤ 8 years	11 years
Communication distance, ≤ 11 AU	30 AU
Solar distance, 1 to 10 AU	0.34 to 30 AU
Optical navigation	
Attitude control, three-axis–stabilized with 2-mrad pointing accuracy	
Data rate, 10 to 30 kilobits per second	
On-board data storage	
Probe delivery or capsule capacity	
Support of and compatibility with instruments selected for flight	

Several different modules are attached to the central module. The interfaces between each of the external modules and the central module will be as mechanically, electrically, thermally, and logically standardized as possible across the mission set. The design of these interfaces thus requires careful consideration of each of the missions as well as of the possible introduction of new technology.

The radio-frequency module includes a fixed high-gain antenna together with its antenna feed and receiver. A study is in progress to determine whether high-gain antennas of different sizes should be carried on different missions or whether it is possible to meet the requirements of all the missions with a single antenna design. One or more low-gain antennas may also be included in the radio-frequency module for use during emergencies if the spacecraft cannot find the Earth.

The propulsion module provides the impulse for trajectory changes and the reaction control for maintaining the proper orientation of the spacecraft. Figure 3 shows the number of tanks necessary to provide trajectory changes of ~ 1 km/sec.

The power module accommodates a radioisotope thermoelectric generator (RTG) or a solar panel. The RTG is the power source of choice for the outer planet missions. Because an RTG is a source of radioactivity, it must be well shielded and located far away from the scientific instruments to minimize interference with their measurements. An RTG cannot be used at all on missions, such as an orbiter of Mars, in which gamma-ray spectrometers are carried for measuring the composition of the target body by analysis of the low flux of gamma rays that it emits naturally. For such missions the power source would therefore be a solar panel. Space must be set aside in the central module for the batteries required when the panels cannot be in sunlight. The power conditioning and handling equipment in the central module would be the same for all missions, independent of the nature of the power source.

The scientific instruments and attitude control sensors are located on the outside of the central module, on one or more fixed booms, or on an articulated platform. The booms are for instruments that must be isolated from interference associated with the main spacecraft. The articulated platform can rotate about either of two axes to allow the instruments on it to be pointed in almost any direction.

The final module would be a probe for a Titan or outer planet mission or the Earth-return capsule for the mission to return a comet sample. The large propellant tanks needed for interplanetary maneuvers would be jettisoned before the probe is released.

Figure 4 illustrates how the spacecraft could be reconfigured from one mission to the next. Figure 4C shows the probe-carrying configuration of Fig. 3. The configuration shown in Fig. 4A could be used for a Saturn orbiter. This mission requires additional propellant tanks, which fit in where the probe was located in Fig. 4C. Figure 4B shows a Mars orbiter configuration, similar to the Saturn orbiter except that a solar panel would replace the RTG power source, whose radiation would interfere with gamma-ray spectrometer observations. The antenna might also be smaller for a Mars mission than for a Saturn mission. The comet and asteroid rendezvous spacecraft would look like that shown in either Fig. 4A or Fig. 4B, depending on

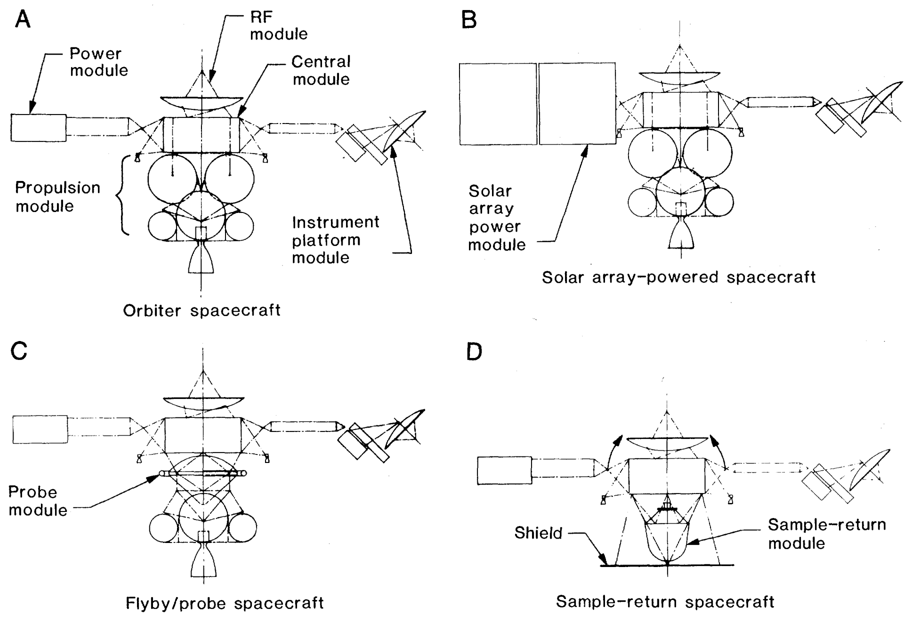

Fig. 4. Reconfiguration of the Mariner Mark II spacecraft from mission to mission. The arrows in (D) indicate two appendages that are to be folded away behind the dust shield during the comet encounter; *RF*, radio frequency.

whether a gamma-ray spectrometer is part of the payload and on how far from the sun the spacecraft must operate. (The latter, in turn, depends on which comet or asteroid is chosen as the target.)

The comet-sampling spacecraft (Fig. 4D) must fly through the cometary dust cloud at high speed. The spacecraft is protected from the dust by a shield and a sample collector. During the flyby the power module and scan platform must be folded back and hidden behind the shield. The shield must be pointed in the direction of the relative velocity vector. If it is necessary to maintain the telemetry link during the flyby, the high-gain antenna would have to be tipped toward Earth.

The requirement for high levels of inheritance and reconfigurability applies to more than just the major spacecraft appendages; it also applies to spacecraft subsystems and the scientific instruments. All missions with high-resolution imaging would use the same Galileo-derived camera design. The other instruments would be treated like "black boxes" as much as possible, with the smallest possible differences in the interfaces for the different instruments. This is made feasible and cost-effective, in part, by the increased use of microprocessors in individual instruments. All but one of the nine Galileo instruments contains a microprocessor. If each Mariner Mark II instrument temporarily stored its own data and formatted it into telemetry packets, the spacecraft data system would not have to be changed in response to changes in the instruments from one mission to the next. Each source-generated data packet contains a standard header identifying its source and length. The spacecraft data system then becomes simply a transportation and storage service. The ground-support system would be based on multimission standards and protocols to such an extent that changes in the science payload or in spacecraft subsystems would be transparent to the machines and people transporting the data. The ground system could support several missions simultaneously.

The modular approach reduces the impact of those changes that must be made. Costs for redesigning, retesting, and flight qualification are minimized. Modularity allows the introduction of new technology into the system piecemeal, as it is proved and qualified. A high level of inheritance enables block buys of items used in several missions. It also simplifies or eliminates the response of the ground system to changes in the spacecraft.

Design margins. To achieve reconfigurability and low cost, adequate design margins are crucial. Design margins provide increments of capability without affecting the overall system design. Adequate margins also lower costs by simplifying designs, manufacturing processes, operations, and sequencing; reducing the amount of performance analysis; and reducing the risk of cost increases associated with design changes.

With respect to Mariner Mark II, large margins have been applied in estimating the performance of its unproved launch vehicles. The analysis that generated the flight times given in Table 1 was based on the pessimistic assumption that the performance of the IUS and the Centaur will be only 80 percent of that expected.

With reasonable mass margins taken into account, the estimated mass of the basic Mariner Mark II spacecraft is about 600 kilograms, exclusive of the propulsion tanks, fuel, and any probes that may be carried. This total includes 97 kilograms for scientific instruments. The estimated mass of a spacecraft inevitably increases during the progression from preliminary design to actual construction. Mass reduction programs required by inadequate initial mass margins have been very expensive. But more important than leaving a margin to cover uncertainties is the ability to "waste" mass to make interfaces simpler and to reduce cost in other ways. The propulsion module is an example of how large mass margins could reduce the cost of the Mariner Mark II missions. If mass had to be minimized, the propellant tanks for each mission would be as small as possible. It would be less expensive, however, to design, build, and test only one or two sizes of tanks and to fill them only partially for missions that require smaller changes in trajectory.

Design margins can also help to reduce the cost of managing power, data storage, computing, and thermal control. For example, the ability to have all instruments and subsystems operate at their peak power levels simultaneously can eliminate a great deal of sequencing activity. Adequate data storage and computing capacities also reduce the amount of detailed planning, sequencing, and memory management.

New technology. Mariner Mark II will make full use of the current gap in planetary missions to take advantage of technical developments. New technology and advanced developments will be used to reduce costs, avoid problems of parts obsolescence, and achieve acceptable performance. The goal is to demonstrate technological readiness through engineering model demonstrations before the start of the project. Several new technologies studied thus far show promise for providing lower recurring costs and a net savings to the project. Examples include the following:

1) An all X-band telemetry system. The Voyager spacecraft receives commands from the ground at the S-band frequency of 2110 megahertz and transmits data in both the S band (~ 2300 MHz) and the X band (~ 8400 MHz). X-band data links are preferred because

directive antenna gain varies directly with frequency squared while noise caused by charged particles along the ray path is an inverse function of frequency squared. The Mariner Mark II two-way X-band system would not only have better performance than the Voyager system, but weight and cost would be reduced because it is simpler and requires less equipment to accommodate one frequency range than two.

2) Fiber-optic rate sensors (FORS) for use as an inertial reference system. A FORS-based inertial reference system has no moving parts and an inherently low drift rate. It might offer distinct cost advantages over the traditional gyroscopes once the integrated optic circuit can be mass-produced. It is expected that, beginning in the late 1980's, industry will invest heavily in the development of fiber-optic components and integrated optic circuits.

3) A multipurpose celestial sensor based on a CCD under microprocessor control. This sensor can image several stars simultaneously to provide a celestial reference for the spacecraft or can be used to track target bodies if mounted on the science instrument scan platform. Closed-loop pointing of this platform might be of particular advantage when the ephemeris of a target body is not well known and might lower costs by reducing sequence planning and platform pointing calibrations.

4) Very large scale integrated (VLSI) circuits. VLSI circuits may be used in command and data handling (CDH) and attitude control subsystems, in interface units between the CDH subsystem and the science instruments, and in other spacecraft subsystems. In one design approach for the CDH subsystem, self-checking computer modules incorporate VLSI and LSI components. VLSI circuits hold promise for reducing the cost, weight, power, and volume of electronic assemblies.

5) Image compression. This is another area where VLSI components could be employed. Newly developed data compression techniques and low error rates allow the number of data bits required to transmit a picture to be reduced by a factor of 1.3 to 4 (depending on the activity of the picture) without any loss of information. There are applications in which much larger compression ratios could be used to trade picture quality for a greater number of pictures. A recent study indicates that optical navigation data can be compressed by a factor as high as 100 without significant degradation of the needed information. Data compression techniques can have a significant impact on downlink telemetry rate, antenna size, transmitter power, and data storage capacity, and therefore on cost.

6) Electronic and optical disk data distribution. If cost-effective, the ground system for Mariner Mark II would allow investigators to have access to their data at remote terminals. This would obviate the need to generate and transport large quantities of hard-copy pictures and magnetic tapes to the data users. There will probably also be significant cost advantages in the use of digital optical disks, which can store an extremely large amount of data and can be reproduced at low cost.

Conclusion

The SSEC is outlining the scientific priorities for planetary exploration in the rest of this century. The Mariner Mark II is being developed to meet the requirements of the deep-space missions on the SSEC's list. The proposed spacecraft could be reconfigured at low cost from mission to mission and be supported by a simplified, multimission ground system. I believe that Mariner Mark II can meet its cost goal of $150 million to $300 million per mission. Discipline will be required to keep the objectives of each mission focused, to limit the complexity and performance of the spacecraft and ground system to the minimum levels required to meet the objectives, and to avoid the use of new technology before its flight readiness has been demonstrated.

After two decades of planetary exploration, we now have the knowledge and experience to select a set of deep-space missions of outstanding scientific value and to implement them at low cost.

References and Notes

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