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Touching Mars: 1998 Status of the Mars Robotic Exploration Program

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Abstract

The Mars Robotic Exploration Program is sending missions every 26 months to orbit and land on Mars and, in 2005, to return a sample to Earth. The highly successful Mars Pathfinder and Mars Global Surveyor missions were launched in 1996. Mars Surveyor '98 will launch in December 1998 and January 1999, to be followed by an orbiter, lander and rover in 2001 and again in 2003. A sample return mission is planned for a 2005 launch. The primary goal of the program after 2001 is the search for evidence of past or present life; and the strategy of orbiters, sample collecting rovers, and sample returns is designed to enrich the chances that such evidence will be discovered. The program is also pioneering "faster, better, cheaper" project management and implementation techniques for NASA. Frequently updated results of the program are available at http://mars.jpl.nasa.gov.

1. Program Objectives

The original strategy for the Mars Surveyor Program was to explore and study Mars in three areas:

- Search for evidence of past or present life
- Understand the climate (weather, processes, and history), and
- Search for resources (environment and utilization)

The exploration of Mars for greater understanding of life, climate, and resources was to focus, in large part, on the study of water and its role in the history of the planet, and the payload selection for the Mars Surveyor '98 orbiter and lander was made around a theme of "volatiles and climate." However, in August of 1996 NASA held a press conference to announce that a team of NASA and non-NASA scientists had discovered possible evidence of ancient life in a Martian meteorite, ALH84001. This highly controversial finding (scientists around the world are in the midst of analysis and experiments to test these results) led to a restructuring of the rationale of the Mars program to focus on the search for life. A team of scientists developed a strategy that involves looking from orbit for likely places where life might have developed, then sending rovers to those sites to collect and store samples, and finally, to return the samples to Earth for analysis with state-of-the-art instruments. The Viking missions showed the futility of sending instruments to look for life in situ, and even the ambiguous evidence of possible life in ALH84001 required the best terrestrial instruments to detect.

The objectives and strategy of the original Mars Exploration Program are described in Reference 1. The programmatic and management processes for the original program are described in Reference 2. Because of the addition of sample returns, which are far more expensive than the orbiters and landers of the Mars Surveyor Program, the Mars Robotic Exploration Program after 1998 has been reformulated with the following objectives:

1. Inspect the surface from orbit to detect terrains that might have harbored life, e.g., ancient sediments and hydrothermal deposits (dry lake beds and hydrothermal vents).

2. Direct instrumented rovers to land at such sites and to detect rocks whose minerology might shed light on whether ancient life might have existed at these sites.

3. With these rovers collect a carefully selected set of rock and soil samples and cache them in a container suitable for retrieval by a later sample return vehicle.

4. Return cached samples to Earth, emplace them in a protected curatorial facility for analysis of possible harmful organisms, and then allocate the samples out for analysis for signs of ancient life. The first set of returned samples is planned to arrive at Earth in 2008.

5. Continue this process of alternating rovers and sample returns through 2016, with rovers launching in 2007 and 2011 and sample returns in 2009 and 2013.

6. If feasible, investigate possible habitats for extant life using these later rover and sample return missions; however, such exploration may require deep subsurface sampling and therefore may be technically intractable by 2013.

2. Program Constraints

2.1 Cost, Schedule and Launch Constraints

The Mars Robotic Exploration Program funding profile has been expanded from that of the original Mars Surveyor Program to accommodate a more ambitious mission set. The funding plans include advanced studies, some technology development, mission design and development, launch vehicles, instrument development, operations development, and operations. While all of these elements are not in a single budget item, the program has been allowed to recommend the reallocation of money between elements and, to some extent, with time. For example, while the launch vehicles for the 1996 and 1998 elements of the program were specified (McDonnell Douglas Delta 7925s and 7425s, respectively) future projects may trade costs between launch vehicle capability and payload mass, thereby reducing overall cost risk.

The program requires that missions be launched in every Mars opportunity; that is, every 26 months. Two elements are required to be launched each opportunity through 2003, with a "single" sample return mission being specified for the 2005 opportunity. Funds available for the program are slightly in excess of $200M per year, including spacecraft, instruments, launch, operations, data analysis, and technology development.

2.2 Solar Power Requirements

The Mars Robotic Exploration Program is precluded from using nuclear power, although small radioisotopic heater units and instrument radioactive sources may be used where required for thermal control or instrument operation. The use of solar power for long-duration missions was proven by Pathfinder to be more difficult than previously expected due to dust settling on the solar arrays. Future missions may be restricted in time and distance explored because of the inherent limitations of solar power.

2.3 Planetary Protection Requirements

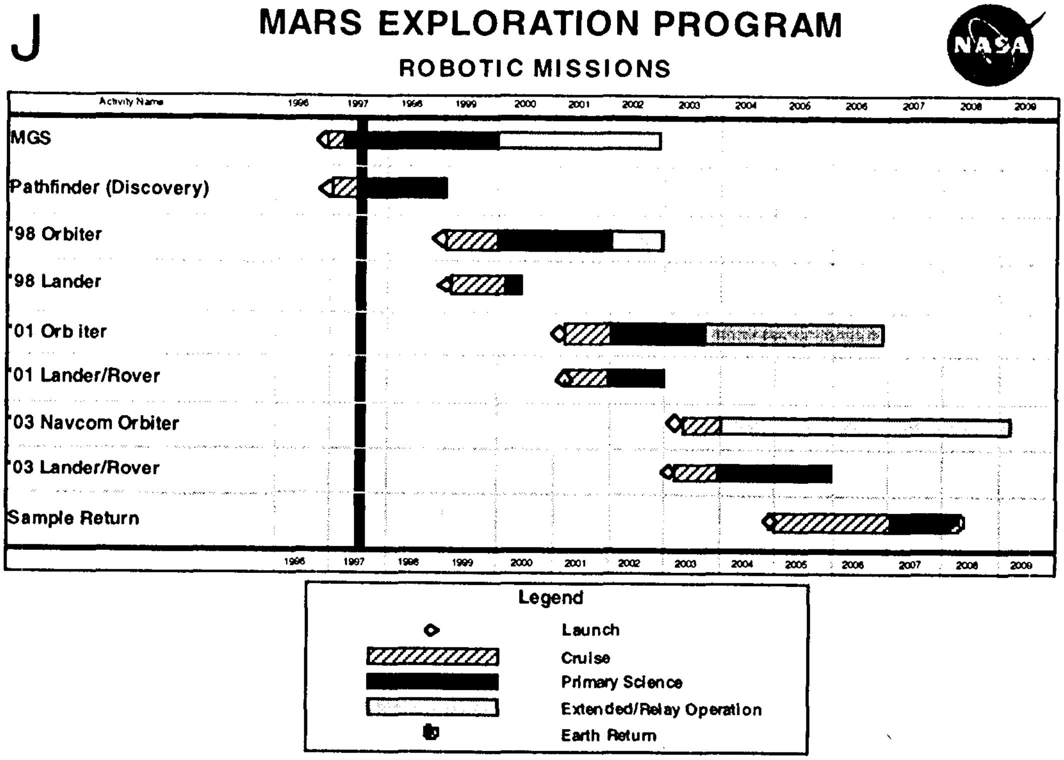
The program is required to follow international planetary protection requirements. In the case of landers, orbiters, and non-sample collecting rovers such as Sojourner, these requirements are relatively simple and can be met by assiduous cleaning and/or trajectory targeting and management. For the 2001 and following landers and rovers the problems are much more difficult because the ultimate objective is to search for life. Therefore, the requirements on "forward contamination" are stringent to ensure that no Earth organisms or chemical markers of such organisms are carried to Mars. Processes are currently being designed and reviewed by the science community.

The issue of "back contamination" is a potentially large driver on the cost of the program past 2001. The requirement is to return no Martian material to the Earth unless it is completely encased within an impregnable container. In addition, facilities must be provided for analyzing the returned samples for potential harmful organisms before they can be released for scientific analysis.

3. The Mars Robotic Exploration Program Missions

Figure 1 shows a schedule of the elements of the Mars Robotic Exploration Program (excluding Pathfinder) through the 2005 sample return mission.

Figure 1



3.1 Mars Pathfinder and Sojourner Rover

The Mars Robotic Exploration Program began with a bang in the winter of 1996 with successful launches on Delta 7925s of Mars Global Surveyor and Mars Pathfinder (a Discovery mission) with its Sojourner rover technology experiment. Both the Pathfinder lander and the Sojourner rover were integrated in-house at JPL. The total cost of the Pathfinder mission, including launch vehicle, rover, instruments, and operations, was approximately $265M. Pathfinder successfully landed, as everyone knows, on July 4, 1997 and studied a Martian flood plain using a multi-spectral imager on the lander and an alpha proton X-ray spectrometer carried by the rover. The Pathfinder mission demonstrated:

- A low-cost entry, descent, and landing system.
- Solar-powered rover and lander surface operations.
- Remote operation of an automated, mobile vehicle.
- Utility of a small rover for scientific investigations.

Scientifically, Mars Pathfinder collected evidence for the long-term presence of water on the Martian surface, analyzed Martian weather at a new landing site, and refined the size of the Martian core. A rover technology experiment discovered that dust falling on the solar array reduced the power output of the array by a fraction of a percent per sol (a Mars day). This has profound implications for the design and lifetime of future missions because the Mas Exploration Program requires the use of solar rather than nuclear power. The Pathfinder mission is described in Reference 3 and its early results in Reference 4.

3.2 Mars Global Surveyor

MGS carries 5 of the 7 instruments that were lost with the failure of Mars Observer in 1993. Mars Global Surveyor successfully entered Mars orbit on September 11, 1997, and began aerobraking to lower the spacecraft from a 45-hour, elliptical orbit to a 2-hour, circular polar mapping orbit. Because of a failure of a damping mechanism during post-launch deployment, the -Y solar panel was damaged. This has resulted in the need for aerobraking to limit the force on the solar array and, consequently, for the aerobraking process to proceed much more slowly than originally planned. This jeopardized the objective of a full Mars year mapping mission in a 2 p.m. orbit. A rapid mission redesign established that by postponing entry into the mapping orbit from March 1998 to March 1999, the mapping mission could be fully accomplished in a 2 a.m. orbit. In addition, this new mission design allows the collection of extensive science data prior to achieving the mapping orbit. The periapsis of the elliptical orbit is lower than the mapping orbit; therefore, resolution of the instruments is improved, although the lighting angles are not ideal.

The elliptical orbit science has already resulted in the discovery of magnetic anomalies on Mars, in measuring seasonal changes in the polar caps, in the discovery that the northern hemisphere of Mars is largely extraordinarily flat, and in understanding the structure of the upper atmosphere. High-resolution images of a variety of never-before-seen structures on Mars have been captured, including images of the terrain near the south pole where Mars Surveyor '98 is planned to land. Early results of the Mars Global Surveyor mission are described in Reference 5. The total cost of MGS, including launch vehicle, instruments, and operations was about $250M.

3.3 Mars Surveyor '98

In December 1998 and January 1999, Mars Surveyor '98 will launch an orbiter (Mars Climate Orbiter) and a lander (Mars Polar Lander), each on a Delta 7425 "Med-lite" launch vehicle. This means that the 1998 spacecraft can only be about half the mass of Pathfinder or MGS. The mission is described in Reference 6. The theme of the Mars Surveyor '98 project is "volatiles and climate." The Mars Climate Orbiter (MCO) will carry a pressure modulated infrared radiometer (PMIRR) to map atmospheric temperature, water vapor, and dust over a full Martian year. This instrument was also previously flown on Mars Observer. In addition MCO will fly a medium-resolution imager for atmospheric images complementary with the PMIRR. The orbiter, like MGS, will enter an elliptical orbit and aerobrake to a polar circular orbit.

The Mars Polar Lander (MPL) will come to rest near the south pole of Mars and will carry a payload, including a 2-meter-long robotic arm, which will excavate Martian history by trenching down through thin layers of dust (and possibly ice) deposited in the layered terrain. Cameras on the end of the robotic arm will image the sides of the trench.

The arm will desposit soil into a thermal evolved gas analyzer on the lander, which will chemically analyze it. A camera system very similar to that on Pathfinder will image the surrounding terrain, and a descent imager will obtain pictures as the lander nears the surface. A Russian-provided LIDAR instrument on the lander will measure atmospheric properties and possibly detect sounds, and a weather station similar to Pathfinder's will measure temperature, pressure, and wind speed. The MPL mission will last for about 90 sols, the time when the Sun is always available for solar power (although low on the horizon) near the south pole.

Two small microlanders are being carried as a technology experiment. The microlanders consist of penetrators enclosed in aeroshells about the size of basketballs. They are to be deployed from the lander before its entry. These are part of the New Millennium program and are called Deep Space-2. They are planned to plummet to the surface without parachutes. Each penetrator is designed to smash through its aeroshell and plunge up to 2 meters into the ground, leaving an aft body at the surface to provide a radio link with the Mars Global Surveyor, which will relay the penetrator's data to the Earth. In addition to information on regolith density, surface and subsurface temperature, and surface pressure, plus the technology performance data (for example, electronics must withstand a force of 80,000 g's), each penetrator is planned to capture a small, subsurface soil sample and analyze it for water content.

The Mars Surveyor '98 orbiter and lander are on schedule for launch. Each will be launched on a Delta 7425. The total cost for the two missions, including the Deep Space-2 penetrators, is less than $300M.

3.4 Mars Surveyor 2001 and 2003

The strategy of the Mars Surveyor 2001 and 2003 missions is to land sample collecting rovers that can cover enough ground to ensure a diverse suite of rock and soil samples will be available for return by the 2005 sample return mission. In addition, the 2001 orbiter is to scout sites to give the best chance that the 2003 lander will be able to find evidence of past life. Because of funding constraints the 2001 and 2003 missions may be integrated into a single project with an overall strategy of maximizing the commonality between the 2001 and 2003 elements.

The current plan for the 2001 and 2003 missions includes an extremely ambitious set of payload and objectives, and the project is in the process of defining options that can fit within the available budget and program funding profile. The 2001 and 2003 missions are to be launched on Delta 7425s, although the 2003 communications orbiter may be launched on a smaller vehicle or stacked with the lander on a Delta 7925. The total cost of the 2001 mission is constrained to be less than $400M for orbiter, lander, and rover.

The final element of the Mars Observer payload (a gamma ray spectrometer) is planned to search for water in 2001 on the Mars Surveyor 2001 orbiter. An infrared radiometer was selected for the orbiter that will search for mineralogical evidence of places that might have harbored life in the past, or for "hot spots" that might be indicative of thermal activity in the present. Although unlikely, such activity might indicate areas that could provide current habitats for organisms. The orbiter has also been directed to fly a copy of 1998 Mars Climate Orbiter's medium-resolution camera. Because the gamma ray spectrometer and the infrared spectrometer have quite different observational lighting and thermal protection requirements, the mission expects to fly in a 4 p.m. or earlier orbit for infrared measurements and a 6 p.m. orbit for gamma ray investigations. The implications of these orbits is that the landed elements, which are currently planned to use the orbiter for communication, will have to communicate in the late afternoon or early morning, and therefore will be dependent on batteries rather than solar arrays for communications.

Because the 2001 opportunity is poorer, energetically, than 1996 and 1998, a new technique is planned for orbit insertion. Instead of using propulsion to slow the orbiter into an elliptical orbit and aerobraking to decrease and circularize the orbit, the 2001 orbiter is intended to aerocapture. This involves enclosing the orbiter in a heat shield and flying it into the atmosphere at just the right angle so that the atmosphere itself brakes the orbiter into a low, circular mapping orbit.

The 2001 and 2003 landers are currently planned to be identical. They are each to land a rover, and also to provide a platform for investigations relevant to future human exploration of Mars under the NASA Human Exploration and Development of Space (HEDS) enterprise. Currently selected HEDS payloads include a radiation experiment (with instruments on both the orbiter and lander), an experiment to understand Mars' possible health hazard for human explorers, and an experiment to understand issues with making fuel from the Martian atmosphere. Each of the latter two experiments include multiple individual experiments and instruments. The health experiment also requires a robotic arm (similar to that on the 1998 lander) to collect soil. The landers will communicate primarily through their own orbiters, although MGS and the 1998 orbiter are capable of being used for communications if they are still functional. Issues with Space Station funding have led to uncertainties in funding for the HEDS payloads for 2001.

The rovers (also planned to be identical between 2001 and 2003 in order to save funds) are to carry a selected payload, called Athena, which comprises a multiple set of instruments to locate, select, collect, and store multiple fresh rock and soil samples. In order to accommodate the Athena payload, and also to range a considerable distance from the lander in search of a variety of sample types, the rovers are much larger and more capable than Sojourner, incorporating the results of several years of technology development. Since they will go "over the horizon" from the landers, the rovers must communicate through the orbiters rather than through the landers as Sojourner did. The rover payload currently includes 14 cameras, an alpha-proton-X-ray spectrometer, a Mossbauer spectrometer, an infrared spectrometer, a "mini-corer" rock collection device, and a container for up to 92 separate samples. In addition, a Raman spectrometer is being developed as a possible candidate for an "add-on" to the rover payload. The 2001 and 2003 rovers will use identical payloads, but a separate selection will be made of investigators for the 2003 experiments.

3.5 Mars Sample Return

Mars Surveyor '05 mission is planned to be the first in a series of missions to return samples from the Martian surface. The current mission design comprises:

a. A Delta III- or Atlas IIAR-class launch vehicle that will launch the complete sample return spacecraft stack.

b. A Mars orbiter that will provide a "cruise stage" for the landed elements and communication for the landed elements, and that houses the Earth-return vehicle.

c. A lander that will carry an ascent vehicle and "fetch" rover and that will use a beacon on the 2001 or 2003 rover to land within a few hundred meters of the cached samples.

d. A "fetch" rover that will go from the lander to the 2001 or 2003 rover and retrieve the sample cache and return it to the ascent vehicle.

e. An ascent vehicle that will launch from the Martian surface, carrying the cache, and rendezvous with the orbiter, transferring the sample cache to the Earth-return vehicle.

f. A container for the sample cache that can be sterilized on the outside and sealed and protected such that no Martian material will be returned to Earth other than that inside the container.

g. An Earth-return vehicle that will launch from Mars orbit, fly to Earth, enter the atmosphere and parachute the sample container to a safe landing in a selected area (perhaps the Utah desert).

h. A sample containment facility where the sample container can be opened and the samples safely tested for evidence of harmful material before the sample is distributed for archiving and analysis.

i. A sample archiving and distribution facility.

A number of conclusions have already been drawn about the sample return mission design based on preliminary design and analysis. Some of the basis for these conclusions is given in Reference 7.

a. Because of energy requirements and within the constraints of the launch vehicle capability, the 2005 sample return will use a Mars on-orbit rendezvous rather a direct ascent and Earth return.

b. The ascent vehicle will carry its own propellants rather than depending on in-situ propellant production (ISPP). Not only is ISPP energetically inferior for the ascent phase, but it requires long surface stay times to generate sufficient propellant for an ascent. Providing considerable power for long periods is especially difficult because of the dust problem identified by Sojourner.

c. While samples will not have to be sterilized prior to return to Earth (providing that a satisfactory container can be implemented), samples may have to be sterilized before being distributed from the containment facility for chemical and mineralogical analysis because of the time required to conclusively demonstrate that no harmful organisms are present in the samples.

d. Implementing a sample return mission within the cost and launch energy constraints requires considerable technology development (see below). In particular improvements in engine efficiency and lightweighting of components are absolutely required. An alternative is being explored with the French: to use an Ariane 5 launch vehicle on a quid-pro-quo basis (see below).

4. Mars Exploration Program Management

4.1 Programmatic Strategy

In February 1994, the Associate Administrator for Space Science announced the start of the Mars Surveyor Program and requested that the Jet Propulsion Laboratory (JPL) proceed to implement the program. In May 1994 the Director of JPL formed the Mars Exploration Program Office to integrate and manage the ongoing Mars exploration robotic missions (Mars Pathfinder and Mars Global Surveyor) and to plan for the implementation of future Mars missions. In August 1996 the scope of JPL's Mars Exploration Program was increased with the formation of the Directorate for Mars Exploration. Subsequently, in October 1996, the Associate Administrator for Space Science assigned Lead Center responsibility to JPL for Mars Exploration robotic missions, and directed the preparation of a plan for executing this responsibility.

The NASA Office of Space Science retains the responsibility for mission and payload selection. JPL has assigned the responsibility for implementing the Mars Robotic Exploration Program to the Mars Exploration Directorate. The Directorate has developed an overall program plan, which is being negotiated with NASA OSS. Implementation includes making trades between launch vehicle costs and mission costs, recommending funding profiles for the various missions, negotiating contracts with spacecraft and instrument builders, developing selected technology peculiar to Mars missions, and managing the projects. Project management includes development, operations, and data analysis and archiving.

4.2 Integrated Operations

In order to save money, the operations of all missions post-Pathfinder have been integrated into a single Mars Surveyor Operations Project (MSOP). The first project being operated by MSOP is MGS, and most of the MSOP team was initially derived from the MGS develoment team. Mission design and navigation and project management are performed at JPL. The spacecraft team is staffed by Lockheed Martin and is located in Denver, Colorado. As was planned for Mars Observer, the instrument teams for MGS are located remotely at the investigators' facilities. The investigators can command their instruments remotely, within their power and data allocations. For instance, they can change data rates. Because of the prolonged MGS aerobraking operations, remote science operations are complicated because the operations system was designed for a 400-km circular, 2 p.m. mapping orbit. The spacecraft is currently in an 11-hour elliptical orbit which is precessing around the planet. In March 1999 the MSOP team expects to be in mapping orbit and MGS operations will be simplified.

A challenge for the MSOP is to accommodate the 1998 missions at the same time that they are completing MGS aerobraking. Cruise operations for the 1998 missions that overlap with MGS aerobraking are expected to be relatively simple. However, operating both the Mars Climate Orbiter and MGS when the former is aerobraking, and also operating the Mars Polar Lander, will require an augmentation to MSOP staffing. Such staffing is being added during the assembly, test, and launch operations (ATLO) phase of the 1998 builds.

An additional challenge will be 2001 and 2003 rover operations. Although the rovers will be relatively autonomous, target selection, sample selection, and supervision of sample collection will require interaction with the Earth. The communication schemes for the orbiter, lander, and rover missions include using the Mars Climate Orbiter and, if it is still operational, the MGS for backup communications. The brief orbital communication windows resulting from the polar circular orbits of all the science orbiters mean that considerable ingenuity is required to depend entirely on relay communications. Direct surface-to-Earth links are being considered for the 2001 and 2003 landers.

4.3 Industrial Partnering

The Mars Exploration Program is being conducted in an industrial partnership mode with industry implementing the orbiter and lander elements of MGS through the 2003 missions. Program management, project management, mission design, and navigation, as well as implementation of some instruments, are the responsibility of JPL. The MGS spacecraft was constructed by Lockheed Martin Astronautics in Denver, Colorado. The Mars Surveyor 1998, 2001, and 2003 orbiters and landers are being or are currently planned to be also constructed by Lockheed Martin Astronautics. This long-term partnership allows much commonality between orbiter and lander electronics in each opportunity and provides a natural evolutionary path from mission to mission for the infusion of new technology and for lessons learned.

The JPL/LMA partnering relationship was featured in the Vice President's 1997 report to the President on reinventing government (Reference 8).

4.4 International Partnering

All Mars Robotic Exploration Missions incorporate international payload elements. Pathfinder included German contributions to the lander imager and the alpha-proton-X-ray spectrometer, plus a Danish magnetic experiment. Mars Global Surveyor incorporates a French radio relay for surface elements. Mars Surveyor '98 includes German contributions to the lander imager, plus Russian elements of the PMIRR and a Russian LIDAR on the lander. The 2001 Athena payload includes international elements, and since 2001 and 2003 will be identical, international partners will participate in the 2003 mission as well.

In 1998 the Japanese are preparing to launch Planet B, a Mars aeronomy orbiter that will be operating at Mars in the same time frame as the U.S. Mars Climate Orbiter. In the early 1990s the European Space Agency (ESA) studied a joint mission with the U.S., called InterMarsNet, to be flown in 2003. That mission was not selected for funding by ESA; however, a mission called Mars Express is being considered by ESA to carry out many of the InterMarsNet orbiter functions and to demonstrate "faster, better, cheaper" techniques of project implementation. Mars Express would also capture much of the science lost with the failure of the Russian Mars '96 mission in November 1996. If Mars Express is implemented, it could provide an orbital communications relay for the 2003 U.S. landed elements. Mars Express may also include a sounding radar experiment to search for subsurface water, an experiment not currently included in the Mars Robotic Exploration Program.

Discussions are also taking place with the French and Italians about possible participation in the 2003 and 2005 missions. The Italians provided Ka-band communication elements for the Cassini mission to Saturn and may be interested in providing orbital communications for the Mars 2003 mission. The French are discussing providing an Ariane 5 launch vehicle for the the 2005 sample return, which would ameliorate somewhat the launch mass constraints and thereby relieve some of the necessity for lightweight technology development. In return, the U.S. could provide mini-landers, based on Deep Space-2 penetrator technology, which would include French instruments, and the French would receive some of the returned samples.

4.5 Science Analysis and Synthesis

The advent of the Mars Robotic Exploration Program has created a need for an ongoing science analysis and synthesis effort for a variety of reasons. Therefore, the program has set aside funding for data calibration and analysis, as well as for timely cross-project analysis and synthesis.

Since missions are launched every 26 months, the design of each mission needs to benefit from the information gained by the previous mission. For example, the discovery by Sojourner of degradation of solar power due to surface dust has impacted the design of the 2001 rover. High-resolution Mars Global Surveyor images of the south polar region are affecting the selection of the landing site for the Mars Polar Lander in 1999 and will be key to the selection of landing sites for 2001 and 2003. But beyond these early findings is the need for more extensive analysis. Upper atmosphere and surface weather profiles will be extended from the Viking results with the results of Pathfinder, MGS, the Mars Climate Orbiter, and the 2001 orbiter. These are important for the design of the sample return mission, including precision landing, which is greatly influenced by winds. But cross-project analysis is required to build up a picture of Mars to influence the design of spacecraft and instruments.

The program is committed to providing data to the science community and public in a timely manner. The most obvious evidence of this is the posting to the Mars exploration web sites of science results immediately after they are obtained. However, individual project funding has been insufficient for complete calibration and archiving of data from each project.

Finally, synthesis of the "state of Mars" is needed to provide the basis of the Mars Educational Outreach Program. Information must be synthesized to give the best possible of the conditions on Mars and its history. This information has to then be turned into curriculum materials for the classroom.

4.6 New Technology Infusion

The infusion of new technology is necessary for all Mars exploration missions in order to accomplish them within the allocated budget. The Mars Pathfinder mission introduced a new flight computer, based on the commercial IBM/Loral RS6000 computer, that will be the basis for the computers of a number of future planetary missions. This provides an enormous increase in computational power over previous missions. Pathfinder also utilized a commercial operating system for its computer, and pioneered a concurrently engineered flight/ground data system that greatly reduced costs. Pathfinder pioneered a low-cost entry and landing approach, of which all but the final airbag impact system is being baselined for future Mars missions.

Mars Global Surveyor is utilizing a composite structure for the spacecraft, although its electronic systems and instruments are inherited from Mars Observer. Operationally, MGS is breaking considerable new ground. The MGS operations team has developed an automated operations process, as well as processes for operating the mission with distributed spacecraft, instrument, and mission/navigation teams. Although aerobraking had been demonstrated at Venus with Magellan, it was performed at the end of the mission when the team was very familiar with the spacecraft's operation. Aerobraking with a new spacecraft at the beginning of orbital operations has been complicated by damage to one of the solar arrays, which are used to provide drag through the upper atmosphere. In addition, the atmosphere of Mars is quite variable—it can "bloom" so that the density at a given altitude can vary by a factor of two over a short period of time. Innovations of the operations team include development of a process whereby atmospheric scientists model in real time the atmospheric conditions between one aerobraking pass and the next to anticipate changes in the Mars atmosphere. This information is used by the navigation and spacecraft teams to decide how deep to penetrate the atmosphere, in a delicate balance between overstressing the damaged solar array and taking too long to achieve a circular mapping orbit. It is also being used to improve the atmospheric models for future aerobraking and aerocapture of orbiters.

The Mars Exploration Technology Program includes precision landing so that payloads can be put at interesting sites and so that the sample return mission can be landed next to a previously landed rover. It is also focussed on low-temperature electronics and batteries and on lightweight technologies for sample return.

The Mars Robotic Exploration Program is dependent on technologies developed by other programs. Specifically, New Millennium's Deep Space-1 is part of a consortium with the Mars program that has developed a small deep space transponder (X-band) that will be used by Mars missions after 1998. The X-2000 program is developing advanced, lightweight electronics systems that will be essential for the Mars sample return mission in 2005 (see Reference 9). NASA's Automation and Robotics program is developing technologies that will be the basis for the 2001 and 2003 rovers.

4.7 Outreach

The Mars Outreach Program is relatively small but has accomplished a great deal. It includes the innovation of having small contracts with universities around the country to train teachers in their area, to develop educational products such as CD-ROMs, and to send students out into their area to educate schools about Mars and space exploration. The program has developed five curriculum modules for middle school children and is in the process of developing several more.

4.8 Preparation for Human Missions

Each of the robotic missions in the Mars Exploration Program will be gathering information needed to plan future human missions to Mars. The robots will find and scout safe and interesting human landing sites, characterize the atmosphere and surface environments so that human missions can be designed properly, look for water and other resources needed by humans, and develop technologies (such as very-low-mass electronics) that will be important for human space flights to Mars.

In addition, there is a specific partnership between the NASA HEDS Enterprise and the Space Science Enterprise to conduct joint missions beginning as early as 2001. Payloads have been selected for possible flight on the 2001 orbiter and lander that would measure the radiation environment, attempt to determine the toxicity of the surface environment, and test technologies needed for in situ propellant production.

4.9 Pushing the Cost and Performance Envelope

Another feature of the Mars Robotic Exploration Program that differs from the original program is the return of ambitious science objectives. The payloads for the 1996 and 1998 missions are relatively modest, which is a major contributor to the low cost of those missions. For 2001, NASA has selected an ambitious payload for orbiter, lander, and rover, as described above. In terms of the overall program, Figure 2 illustrates the progression of the number of experiments to be performed per mission. (Experiments, for this purpose, are instruments or instrument-supporting elements such as robotic arms or small rovers. The large 2001 Athena rover is an independent spacecraft.)

Figure 2

Number of Experiments per Mission

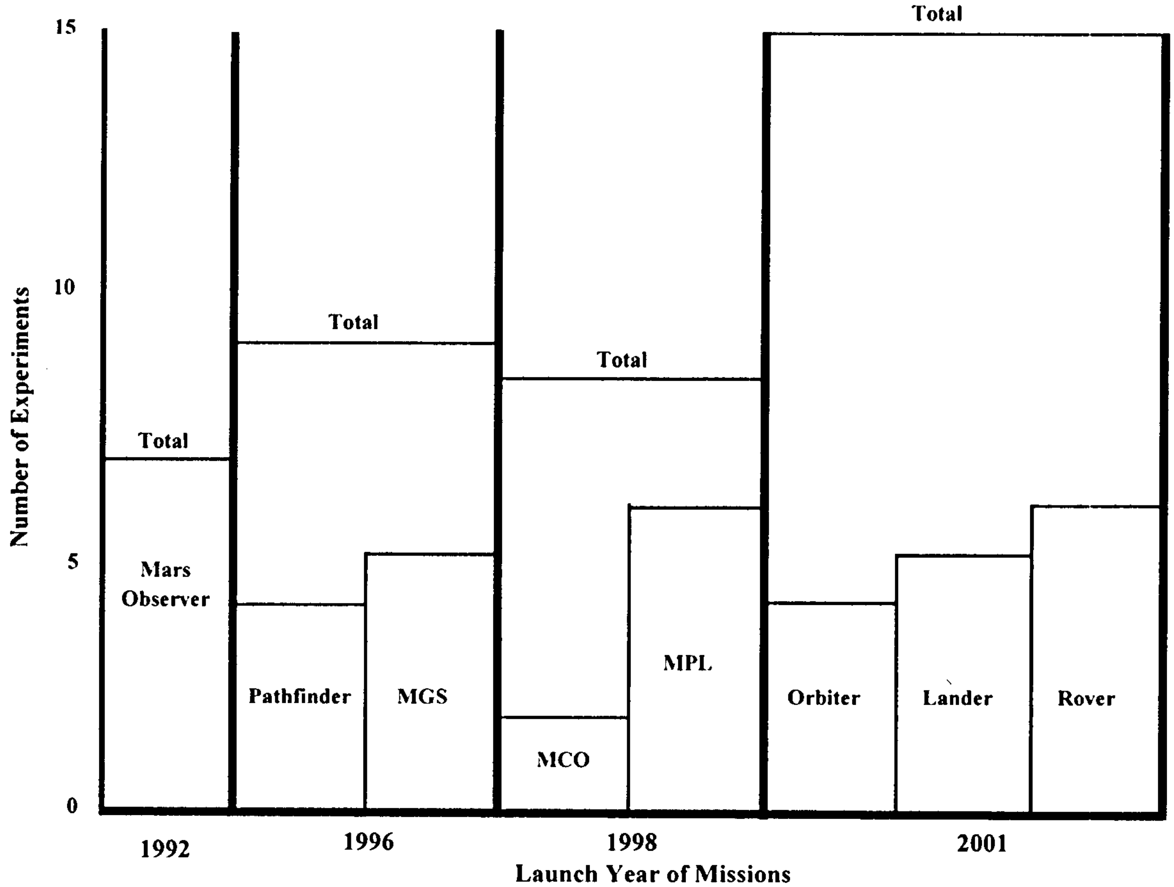
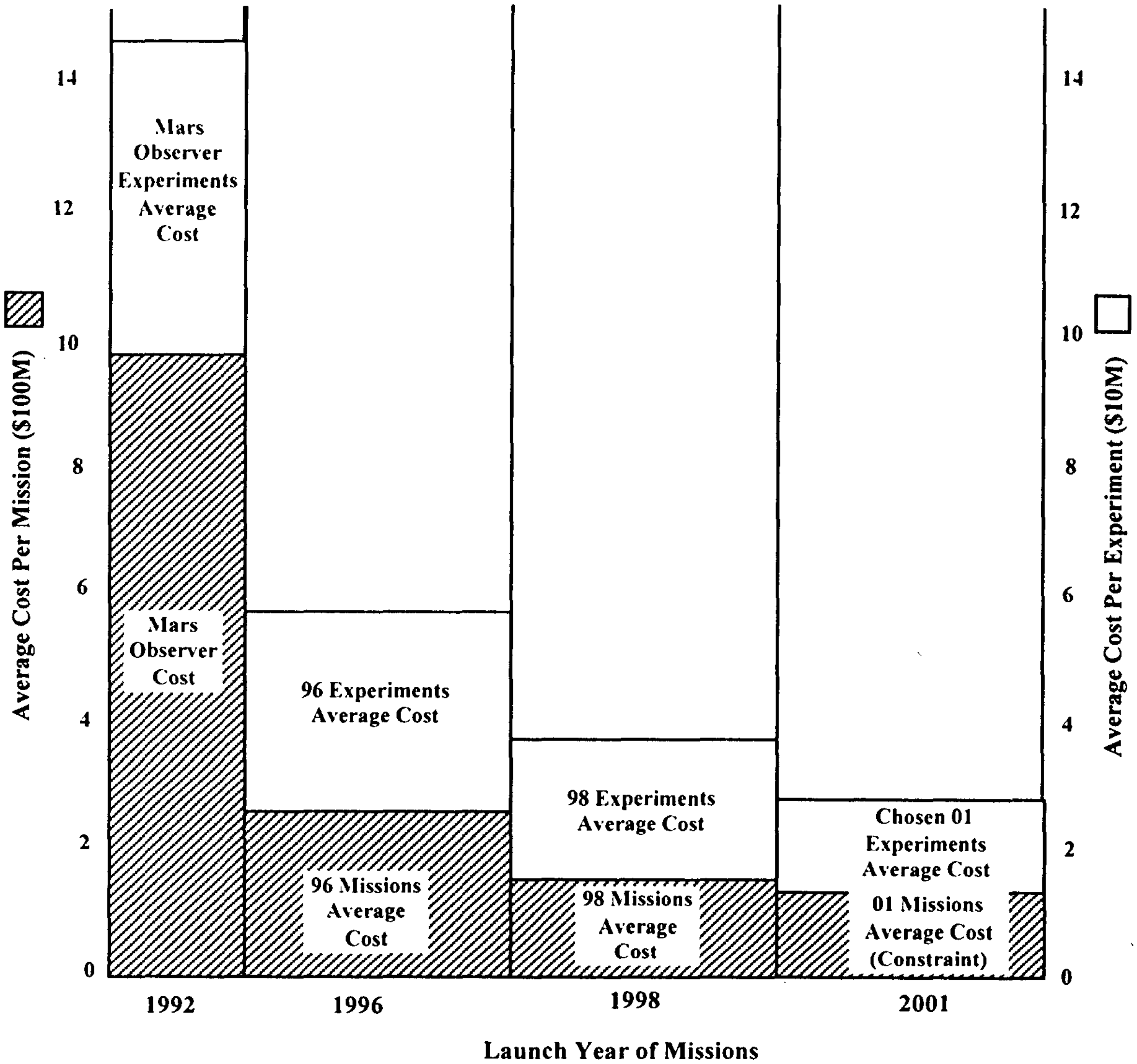


Figure 2 shows a large increase in the selected number of experiments between the 1992 and 1996/98 missions and the 2001 mission. Mars Observer flew seven experiments. Pathfinder carried four experiments (including the rover), MGS five. The 1998 Mars Climate Orbiter is flying two experiments, the Mars Polar Lander has six, including the robotic arm. In 2001, fifteen experiments have been selected for the orbiter, lander, and rover.

Figure 3 illustrates how the average cost per mission and per experiment has declined from 1992 to 2001 (assuming that all the selected 2001 experiments can be accommodated).

Figure 3

Average Cost per Mission and Average Cost per Experiment



Mars Observer total cost in real year dollars was about $980M. Average mission cost in the 1996 opportunity was about $260M. In 1998 that average cost declined to about $165M, largely due to commonality between the two spacecraft, which was not possible in 1996. For 2001, the allocation for three missions (orbiter, instrumented lander, and rover) is an average of $140M.

The experiment cost is calculated by dividing the total mission cost by the total number of experiments. Mars Observer experiments averaged about $143M apiece. The 1996 missions averaged about $60M per experiment. In 1998, the per-experiment cost was about $37M. If it is feasible to accommodate all the selected experiments on the 2001 mission, the average cost per experiment would be only $28M. The complexity of the

2001 mission is approaching the complexity of the Galileo and Cassini missions, which have an average mission cost of well over $1B, and greatly exceeds the complexity of the $1B Mars Observer mission. The challenge for 2001 and the following missions is severe.

5. Conclusions

The Mars Robotic Exploration Program is leading the way for NASA's conversion to a faster, better, cheaper way of conducting its programs. Mars Pathfinder and Mars Global Surveyor have demonstrated that excellent science and high public interest can be accomplished for a fraction of the cost of previous missions. The program is following a science strategy that, if future missions can be accomplished within the very tight cost constraints, will result in the return of a sample to Earth by 2008. There may need to be trade-offs, however, between the amount of in-situ science to be conducted on each mission vs the probability of returning a sample. Trade-offs will also have to be made on the amount of preparation for human missions to be accomplished in the next decade vs the amount of scientific information to be garnered.

6. Acknowledgment

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7. References

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