Mars Program

Independent Assessment Team

Summary Report

March 14, 2000

Mars Climate Orbiter failed to achieve Mars orbit on September 23, 1999. On December 3, 1999, Mars Polar Lander and two Deep Space 2 microprobes failed. As a result, the NASA Administrator established the Mars Program Independent Assessment Team (MPIAT) with the following charter:

Review and Analyze Successes and Failures of Recent Mars and Deep Space Missions

- Mars Global Surveyor
- Pathfinder
- Deep Space 1
- Mars Climate Orbiter
- Mars Polar Lander
- Deep Space 2

Examine the Relationship Between and Among

- NASA Jet Propulsion Laboratory (JPL)
- California Institute of Technology (Caltech)
- NASA Headquarters
- Industry Partners

Assess Effectiveness of Involvement of Scientists

Identify Lessons Learned From Successes and Failures

Review Revised Mars Surveyor Program to Assure Lessons Learned Are Utilized

Oversee Mars Polar Lander and Deep Space 2 Failure Reviews

Complete by March 15, 2000

In-depth reviews were conducted at NASA Headquarters, JPL, and Lockheed Martin Astronautics (LMA). Structured reviews, informal sessions with numerous Mars Program participants, and extensive debate and discussion within the MPIAT establish the basis for this report. The review process began on January 7, 2000, and concluded with a briefing to the NASA Administrator on March 14, 2000.

This report represents the integrated views of the members of the MPIAT who are identified in the appendix. In total, three related reports have been produced: this report, a more detailed report titled “Mars Program Independent Assessment Team Report” (dated March 14, 2000), and the “Report on the Loss of the Mars Polar Lander and Deep Space 2 Missions” (dated March 22, 2000).

Review and Analyze Successes and Failures of Recent Mars and Deep Space Missions

The Mars and deep space missions, reviewed and analyzed by this team, were implemented over a period of about 6 years (1994–present). Mars Global Surveyor (MGS) was launched in 1996 and was the first Mars mission to employ some tenets of Faster, Better, Cheaper (FBC). MGS is an extraordinary success and continues to be a highly productive science mission.

Mars Pathfinder was launched in 1996, landed on Mars on July 4, 1997, and captured the excitement of the public with lander and rover operations on the Mars surface. It was the first complete Mars FBC mission and was an engineering, science, and public success.

Deep Space 1 (DS-1) was a successful technology mission launched in 1998. It provided a space demonstration of numerous new technologies, including ion propulsion and onboard autonomous operations. These technologies are now space proven and available for future deep space missions.

Mars Climate Orbiter (MCO) was launched in late 1998, followed by Mars Polar Lander (MPL) and Deep Space 2 launched in early 1999. MCO failed to achieve Mars orbit because of a navigation error, resulting in the spacecraft entering the Mars atmosphere instead of going into the planned orbit. The “Report on the Loss of the Mars Climate Orbiter Mission,” dated November 11, 1999, and the “MCO Mishap Investigation Board Phase I Report,” dated November 10, 1999, provide details on the failure cause and corrective action.

The following is a summary of the MCO findings. Spacecraft operating data needed for navigation were provided to the JPL navigation team by prime contractor Lockheed Martin in English units rather than the specified metric units. This was the direct cause of the failure. However, it is important to recognize that space missions are a “one strike and you are out” activity. Thousands of functions can be correctly performed and one mistake can be mission catastrophic. Mistakes are prevented by oversight, test, and independent analysis, which were deficient for MCO.

Specifically, software testing was inadequate. Equally important, the navigation team was understaffed, did not understand the spacecraft, and was inadequately trained. Navigation anomalies (caused by the same units error) observed during cruise from Earth to Mars were not adequately pursued to determine the cause, and the opportunity to do a final trajectory correction maneuver was not utilized because of inadequate preparation.

MPL and the two Deep Space 2 microprobes were integrated on a common cruise stage for the trip from Earth to Mars. Separation of the microprobes and the lander was planned to occur about 10 minutes prior to the planned Mars landings. The design of the lander precluded any communications from the period shortly before separation from the cruise stage until after Mars landing. The planned communications after landing did not occur, resulting in the determination that the MPL mission had failed. Extensive reviews, analyses, and tests have been conducted to determine the most probable cause of the MPL failure. This is documented in the “Report on the Loss of the Mars Polar Lander and Deep Space 2 Missions.” Several possible failure causes are presented, which include loss of control due to spacecraft dynamic effects or fuel migration, local characteristics of the landing site beyond the capabilities of the lander, and the parachute covering the lander after touchdown. Extensive tests have demonstrated that the most probable cause of the failure is that spurious signals were generated when the lander legs were deployed during descent. The spurious signals gave a false indication that the lander had landed, resulting in a premature shutdown of the lander engines and the destruction of the lander when it crashed into the Mars surface.

Without any entry, descent, and landing telemetry data, there is no way to know whether the lander reached the terminal descent propulsion phase. If it did successfully reach this phase, it is almost certain that premature engine shutdown occurred.

It is not uncommon for sensors involved with mechanical operations, such as the lander leg deployment, to produce spurious signals. For MPL, there was no software requirement to clear spurious signals prior to using the sensor information to determine that landing had occurred. During the test of the lander system, the sensors were incorrectly wired due to a design error. As a result, the spurious signals were not identified by the systems test, and the systems test was not repeated with properly wired touchdown sensors. While the most probable direct cause of the failure is premature engine shutdown, it is important to note that the underlying cause is inadequate software design and systems test.

Deep Space 2 (DS-2) was a technology mission to demonstrate microprobe technology for future applications in exploring various solid bodies in our solar system. The DS-2 design provided no data from the time it was integrated on the cruise stage at the launch site until after the Mars landing; therefore, there is no knowledge of probe health following cruise stage integration. No communications were received after the expected landings, resulting in the determination that the two DS-2 microprobes failed. Reviews and analyses of the DS-2 development process have been performed and are documented in the earlier referenced “Report on the Loss of the Mars Polar Lander and Deep Space 2 Missions.”

DS-2 had an inadequate test program that deviated significantly from the proven practice of “test-as-you-fly, fly-as-you-test.” No “most probable cause” has been identified for the DS-2 microprobes; however, it is clear that the microprobes were not adequately tested and were not ready for launch.

The discussion on the previous pages summarizes the three successful and three unsuccessful Mars and deep space missions reviewed and analyzed by the MPIAT. The important question is: “What are the lessons learned from these successes and failures?”

There are common characteristics of the successful missions and of the unsuccessful missions. The following summarizes the lessons learned from the MPIAT review of these missions.

Experienced project management or mentoring is essential.

Deep space missions are inherently difficult. These difficulties include long-duration operations, precision navigation, hazardous environments, landing sites with unknown hazards at the scale of the lander, and, in many situations, the first use of sophisticated hardware and software. Launch schedules typically have little flexibility. As an example, Mars launch opportunities are approximately 1 month long and are separated by about 26 months.

The management challenges are enormous. MGS and Pathfinder had experienced project managers who contributed significantly to their successes. DS-1 had a competent, but inexperienced, project manager who was augmented by senior JPL management. MCO, MPL, and DS-2 had competent, but inexperienced, project managers. The lack of senior management involvement to compensate for the lack of experience contributed to the MCO, MPL, and DS-2 failures.

The number of JPL projects has increased significantly. There are not enough experienced managers for the large number of projects for which JPL is currently responsible. This situation requires significant involvement by senior management to compensate for the lack of experience.

Project manager must be responsible and accountable for all aspects of mission success.

For MGS, Pathfinder, DS-1, and DS-2, the project managers were responsible for all aspects of their projects, from project formulation through completion of mission operations. The MCO and MPL project manager was responsible for development only, with a separate organization and project manager responsible for operations after launch. This arrangement contributed to the MCO failure.

Unique constraints of deep space missions demand adequate margins.

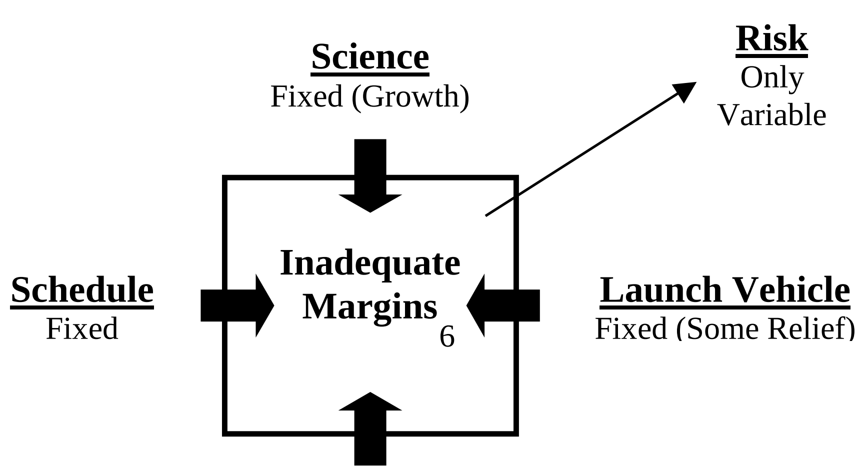
Deep space missions are characterized by a fixed launch date (which fixes the schedule), a given launch vehicle (which fixes the available weight), competitively selected science payloads (which establish the performance requirements), and for the missions that were analyzed, fixed cost. When these four constraining parameters are fixed, there are only two remaining variables—margins and risk. If adequate margins are available, risk can be effectively managed; if not, risk will grow to an unacceptable level.

MGS and Pathfinder had adequate margins, and the risks were effectively managed, contributing to successful missions. The technology mission, DS-1, did not have adequate margins; however, relief was provided because this was not a science-driven planetary mission with a fixed launch opportunity. DS-1 performance requirements were effectively descoped, and the launch schedule was delayed several months. Without this performance and schedule flexibility, DS-1 would have had excessive risk.

MCO, MPL, and DS-2 did not have adequate margins. MCO and MPL were managed as a single Mars ’98 project. The project was significantly underfunded from the start for the established performance requirements. By comparison, MGS was a single orbiter with science instruments and several subsystems developed for an earlier mission (Mars Observer). The development cost plus the estimated value of the inheritance was approximately $250 million. Pathfinder is the standard for a Mars FBC mission. Development cost for Pathfinder was about $200 million, including $25 million for the rover. Mars ’98, which included an orbiter, a lander, and about three times as much science as Pathfinder, cost about $190 million. All costs are constant-year 1999 dollars to allow for a direct comparison.

Mars ’98 (which included both MCO and MPL) cost approximately the same as Pathfinder. This clearly indicates the significant lack of sufficient budget for Mars ’98. It was underfunded by at least 30 percent. There were many reasons for the underfunding, including an aggressive proposal from LMA.

The selection of a launch vehicle with little margin, some growth in the science payload, and the fixed planetary launch window also contributed to inadequate margins. The result was analysis and testing deficiencies as well as inadequate preparations for mission operations. These resulted in excessive risk and contributed to the failures. This is illustrated for Mars ’98 in the following figure.



Appropriate application of institutional expertise is critical for mission success.

For more than four decades, significant investments have been made in developing the deep space capabilities at JPL. As a result, JPL is a center of excellence for deep space exploration. A primary reason for doing deep space missions at JPL is to take advantage of this unique capability. This expertise was effectively used for MGS, Pathfinder, and (to some degree) DS-1, resulting in a significant contribution to the success of these missions. Use of the JPL capabilities was significantly curtailed on Mars ’98 largely because of funding limitations. Consequently, a significant opportunity was missed that may have resulted in recognition of inadequate margins and excessive risk in the Mars ’98 project. JPL institutional support for DS-2 varied considerably, but was inadequate for the technical complexity of the microprobes.

National capabilities can also contribute to the success of deep space missions. As an example, the atmospheric entry expertise at NASA’s Langley Research Center, Ames Research Center, and LMA was the primary source of this capability for Pathfinder. The air bag technology for Pathfinder came from Sandia National Laboratory. Industry, academia, NASA Centers, and other Government organizations were also important participants in DS-1.

A thorough test and verification program is essential for mission success.

FBC encourages taking prudent risk in utilizing new technology and pursuing important science objectives and innovation. However, risk associated with deviating from sound principles should not be allowed. Sound principles include:

Efficient, competent, independent reviews

Oversight, analysis, and test to “eliminate” a single human mistake from causing mission failure

Clear definition of responsibilities and authority

Prudent use of redundancy

Test-as-you-fly, fly-as-you-test

Risk assessment and management

This is not an exhaustive list, but rather important examples.

MGS and Pathfinder rigorously followed sound principles. DS-1 execution was mixed. DS-2 deviated to such a degree that it leads to the conclusion that the microprobes were not ready to launch. Mars ’98 did the best that could be done with the limited resources, but deviated significantly in analysis, testing, and the conduct of reviews.

Effective risk identification and management are critical to assure successful deep space missions.

Risk is inherent in deep space missions. Effective identification and management of risk are critical responsibilities of project management and often determine whether a mission will be successful. This was clearly a problem in the implementation of MCO, MPL, and DS-2.

Faster, Better, Cheaper encourages taking prudent risk where justified by the return. The MPIAT found that the lack of an established definition of FBC and policies/procedures to guide implementation resulted in project managers having different interpretations of what is prudent risk. Senior management needs to establish that risk associated with new high-return technology and innovation is acceptable as is risk associated with pursuing high-value science. Risk associated with deviating from sound principles is unacceptable. Risk must be assessed and accepted by all accountable parties, including senior management, program management, and project management. All projects should utilize established risk management tools such as fault tree analysis and failure effects and criticality analysis.

Institutional management must be accountable for policies and procedures that assure a high level of mission success.

Institutional management must assure project implementation consistent with required policies and procedures.

Senior management is responsible and accountable to establish standards for the conduct of deep space missions; to assure that these standards are being followed; to assure that adequate resources, including institutional expertise, are available and used; and to assure that projects are being implemented with prudent risk. In the case of Mars ’98, this did not happen at NASA Headquarters, JPL, or LMA. A clear example is the absence of critical entry, descent, and landing telemetry on MPL.

MGS and Pathfinder success can be directly attributed to the experienced project managers and their effective use of expertise from numerous sources. JPL senior management contributed significantly to the success of DS-1.

Telemetry coverage of critical events is necessary for analysis and ability to incorporate information in follow-on projects.

The lack of communications (telemetry) to provide entry, descent, and landing data for MPL was a major mistake. Absence of this information prevented an analysis of the performance of MPL and eliminated any ability to reflect knowledge gained from MPL in future missions. It is a prime example of the Mars Program being treated as a collection of individual projects as opposed to an integrated program.

The final observation that needs to be made is:

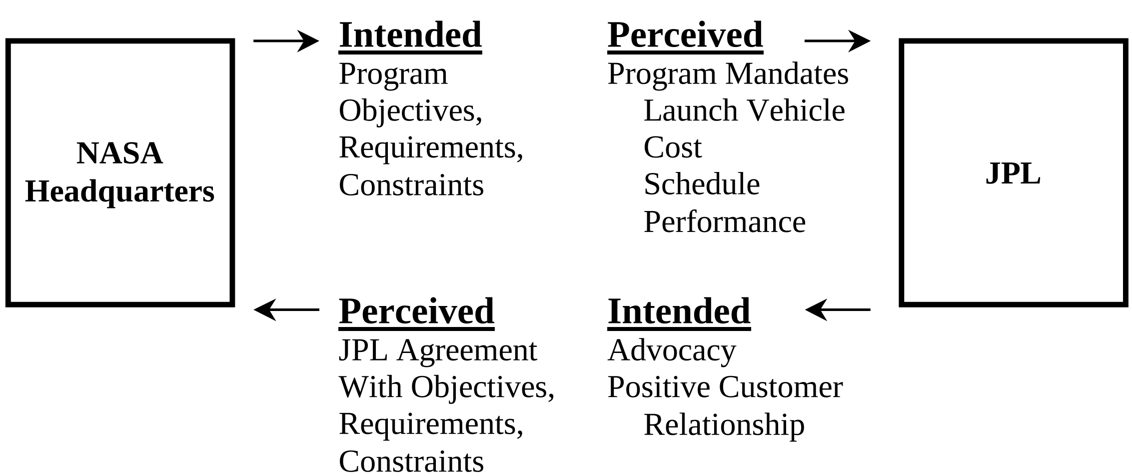
If not ready—do not launch.

Planetary launch opportunities are typically separated by periods of many months or years; Mars launch opportunities are approximately every 26 months. Not being ready for a scheduled launch opportunity is serious, but not as serious as proceeding without being ready. Senior management needs to make it unambiguously clear that "if not ready—do not launch."

Interfaces and Relationships

The MPIAT charter includes an examination of relationships among JPL, Caltech, NASA Headquarters, and Lockheed Martin. An assessment of the effectiveness of the involvement of scientists was also required. Among the interfaces and relationships reviewed, two significant areas of concern were identified: "The interface between NASA Headquarters and JPL" and "The interface between JPL and Lockheed Martin."

The interface between NASA Headquarters and JPL was found to be highly ineffective. A simplified example of the ineffectiveness of this interface is illustrated in the following figure comparing intended versus perceived communications.



NASA Headquarters provided objectives, requirements, and constraints for the Mars Program and projects to JPL. They appropriately considered this a Headquarters responsibility. JPL interpreted these objectives, requirements, and constraints as launch vehicle, cost, schedule, and performance mandates. As an example, for Mars ’98, the JPL management perception was that no cost increase was possible. The response from JPL was more one of advocacy for the program and presenting a positive image to the customer (NASA Headquarters) than a rigorous risk assessment with appropriate concerns expressed. What NASA Headquarters understood was JPL agreement with the objectives, requirements, and constraints. The result was an ineffective interface that did not resolve issues or manage risk. This directly contributed to inadequate margins for Mars ’98, which in turn contributed to the MCO and MPL failures. The lessons learned from an analysis of this relationship are:

> **Frank communication of objectives, requirements, constraints, and risk assessment throughout all phases of the program is critical to successful program/project implementation.**
>
> **Senior management must be receptive to communications of problems and risks.**

Another aspect of the interface was the absence of a single Mars Program interface at NASA Headquarters responsible for all requirements, including those from other NASA organizations. Absence of a single interface resulted in multiple inputs to the JPL Mars Program that were in some instances conflicting and in general added to the confusion and poor communications. The lesson learned is:

> **A dedicated single interface at NASA Headquarters for the Mars Program is essential. This individual should have responsibility for all requirements (including human exploration) and funds. The position should report to the Associate Administrator for Space Science.**

The day-to-day relationship between JPL and LMA was positive during the conduct of the Mars ’98 project. However, the relationship was ineffective when it came to informing senior management about risk. Lockheed Martin senior management did not formally identify risk or deviations from acceptable practice. The lesson learned is:

> **Contractor (Lockheed Martin) responsibilities must include formal notification to the customer (NASA/JPL) of project risk and deviations from acceptable practice.**

Mars Program Implementation

The final responsibility identified by the charter is a review of the Mars Program to assure that the identified lessons learned are utilized.

JPL has historically been responsible for individual projects. With NASA delegating program management responsibilities from NASA Headquarters to the NASA Centers in 1996, JPL was assigned this responsibility for the Mars Surveyor Program.

The MPIAT does not believe that the Mars Program has been effectively managed. It has been managed as a collection of individual projects rather than as an integrated framework in which projects fit to accomplish more than the sum of individual projects. Not including entry, descent, and landing telemetry is a prime example of this deficiency.

As a result of moving to the FBC concept, the number of flight projects at JPL has increased over a 3-year period from a historical average of 1 to 4 in a given year to a current level of 10 to 15 at the same time. This increase is a result of the FBC approach, which has as its objective smaller spacecraft with more frequent missions. This increase in the number of projects requires additional capable project managers. There has been a loss of experienced, successful project managers through retirement. The net effect is to use competent, but inexperienced, managers for the increased number of projects. An earlier lesson learned is the need for senior management involvement and mentoring to compensate for the lack of experience.

Currently, all flight projects, the Mars Program, and numerous other instrument and program responsibilities are in one organization at JPL. This results in an extraordinary workload and span of control for this organization.

The conclusion of the MPIAT is that the current organization at JPL is not appropriate to successfully manage the Mars Program in combination with other commitments for the reasons discussed above. The following organizational changes would be responsive to this concern:

Establish an integrated Mars Program Office at JPL reporting to the Laboratory Director.

Establish a new, independent organization at the Directorate level dedicated to implementing major flight projects.

Summary

Based upon intensive review by the MPIAT, there are several general observations important to the future Mars Program:

Mars Exploration Is an Important National Goal That Should Continue.

Deep Space Exploration Is Inherently Challenging. The Risks Are Manageable and Acceptable.

NASA, JPL, and Industry Have the Required Capabilities to Implement a Successful Mars Exploration Program.

JPL Is a Center of Excellence for Deep Space Exploration with Unique Capabilities.

Faster, Better, Cheaper, Properly Applied, Is an Effective Concept for Guiding Program Implementation that Should Continue.

Significant Flaws Were Identified in the Formulation and Execution of the Mars Program.

All Identified Flaws Are Correctable in a Timely Manner to Allow a Comprehensive Mars Exploration Program to Successfully Continue.

Appendix

MPIAT Membership

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