THE MARS EXPLORATION ROVER PROJECT

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ABSTRACT

The twin rovers of the Mars Exploration Rover Project successfully landed on the surface of Mars in January 2004, and initiated a highly successful science and exploration campaign. This marked the culmination of an unprecedented four-year effort to design, build, launch, and operate two of the most complex planetary spacecraft ever built. The project was started in the aftermath of the 1999 Mars mission failures, and was commissioned to take advantage of the highly advantageous 2003 opportunity. The development schedule from project start to launch was only 35 months, so schedule management was the most significant challenge facing the project. This problem was compounded when early assumptions about the extent of design heritage from Mars Pathfinder proved to be flawed. The project derived a number of useful lessons learned in solving these challenges that can be applied to future missions.

PROJECT FORMULATION

The MER Project was started in May 2000 during the turbulent period following the loss of the Mars Climate Orbiter and Mars Polar Lander missions. NASA initiated an effort to restructure the Mars Exploration Program, but recognized the need to take rapid advantage of the excellent 2003 opportunity. Two missions were identified as strong candidates for 2003: a large orbiter to follow on the Mars Odyssey mission or a rover mission based on the successful Mars Pathfinder mission. After a short study period, NASA decided to proceed ahead with the rover mission in July 2000. The rationale for this decision included some of the following elements:

- The 2003 opportunity was ideal for a lander mission, with good geometry and energetic considerations for both launch and arrival

- The orbiter concept would be very difficult programmatically because neither the spacecraft provider nor payload elements had been selected

- The rover concept was relatively mature because of the Mars Pathfinder heritage and because the science payload could be inherited from the Athena Rover study

The recent failure of Mars Polar Lander, however, had made a number of people concerned about the wisdom of sending a single vehicle into the harsh and unpredictable Martian environment. This concern resulted in a redirection of the project to build and launch two identical rovers to reduce risk and improve science return.

Thus, the MER Project was initiated with the objective of placing two highly capable rovers on the surface of Mars with primary purpose to look for geologic evidence of ancient water. Each rover would carry a payload package consisting of a stereo pair of high resolution color cameras (PanCam), a minature Thermal Emission Spectrometer (MiniTES) similar to the instrument flown on the Mars Global Surveyor spacecraft, a Mossbauer Spectrometer contributed by the Max Planck Institute for Chemistry in Germany, an Alpha Particle X-ray Spectrometer similar to the instrument flown on the Mars Pathfinder Sojourner Rover (also contributed by the Max Planck Institute), a Microscopic Imager, a set of magnets for magnetic properties assessment (contributed by the Danish XXXX), and a Rock Abrasion Tool to enable sub surface rock analysis. The key Level 1 requirements negotiated with the Mars Exploration Program were:

- Launch two rovers to Mars in 2003 opportunity on Delta II-class launch vehicle
- Provide real time communications during Mars entry & landing to support fault reconstruction
- Land and operate solar powered rovers in latitude band ±10 deg around the subsolar point
- Operate each rover for at least 90 Sols
- Utilize both X-band Direct to Earth and UHF communications through Odyssey
- Drive the rovers to at least 8 separate locations and investigate geologic context & diversity
- Drive more than 600 m on at least one rover

IMPLEMENTATION CHALLENGES

The planned and actual implementation chronologies of the MER Project are shown in Figure 1. During the early implementation phase, the project team focused on validating the basic mission concept. This effort led to the realization that the concept and underlying programmatic assumptions were not consistent. MER was based on the presumptions that the Mars Pathfinder Entry, Descent, and Landing approach could be inherited and that a large and capable rover would fit within the technical resource (mass, power, volume) envelope provided by the Pathfinder landing system. Both assumptions proved to be wrong. The Mars Pathfinder EDL system was developed in a Faster, Better, Cheaper era and while the resulting mission was successful, there were aspects of the development process that were not appropriate for a high visibility, post-failure effort. In addition, the environmental assumptions around which the Pathfinder system was designed (winds, site altitude, Earth-Mars geometry) were not valid for the 2003 opportunity. These changes alone would have forced some changes to the build-to-print approach.

The more significant impact on heritage, however, came from the mismatch between the Pathfinder delivery systems resource capability and the requirements of the Athena Rover. An assumption made during concept development was that the project would operate in a capabilities driven/resource constrained environment. In that model, the rover, science payload, and mission return would be descoped to fit within the

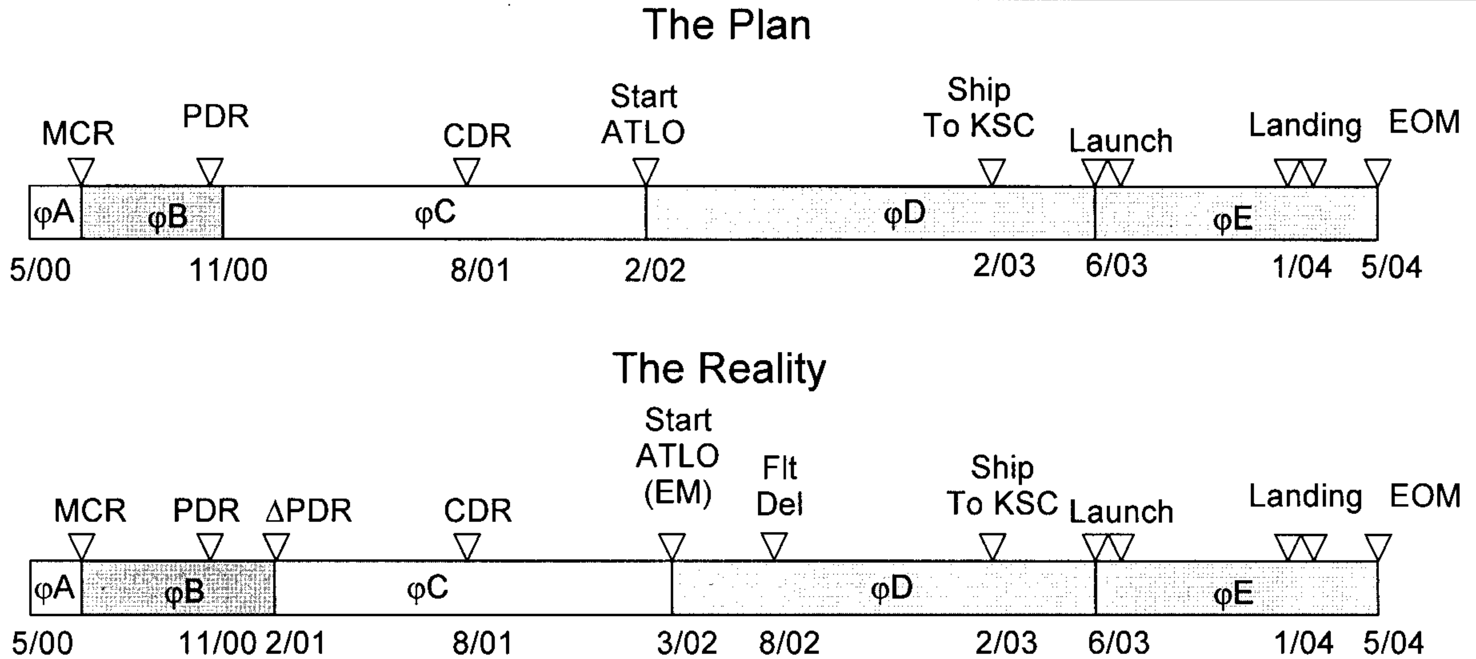

Figure 1 MER Implementation Chronology

heritage envelope. The paradigm established by the Mars Program however, was a science driven model. Thus, the project had to redesign the EDL system to rectify the capability mismatch and preserve the science return. The basic architecture (parachute, airbags, RAD rockets) remained similar (which proved to be critically important), but the build-to-print programmatic plan was broken.

The project recognized this fundamental programmatic flaw in late 2000 and developed a technical recovery plan by early the following year. Significant changes were made to the design of the parachute, terminal descent rocket system, lander structure, and airbags. The parachute and airbags were modified to increase the landed mass capability, while the lander structure was changed from an all aluminum design to a composite approach to reduce mass. Additional terminal descent rockets were added to control horizontal landing velocity and decrease dependence on landing site winds. All four efforts became significant development challenges that aggravated an already tight development schedule.

The cost and schedule implications of the loss of heritage were not fully realized until several months later, near the time of the Project Critical Design Review. The net result of the change in the technical baseline was the loss of 4-5 months on the critical path. The project invested significant budget resources to buy back some of that lost schedule, and had to adopt a two shift, six day a week plan for spacecraft Assembly, Test, and Launch Operations (ATLO). The change in the ATLO plan, in particular, allowed us to make up virtually all of the schedule slip.

QUALITY CHALLENGES

The combination of the tight schedule and the reaction to the Mars 98/99 failures meant that the Project had an extreme focus on maintaining acceptable quality and mission risk. The Project's philosophy was to assure a risk level commensurate with previous Class A flagship missions (Cassini, Galileo, etc.). This did not mean, however, that it was okay to take risks that had been acceptable in the past. The project team evaluated the technical design, programmatic plans, and verification approach from first principles to determine the overall risk posture. A good example is the overall Entry, Descent, and Landing system. Although there turned out to be limited component heritage from Mars Pathfinder, the system architecture remained similar. The project, however, did not take any short cuts in either the design process or verification program. The result is that we went back and challenged many of the assumptions & conclusions reached by the Mars Pathfinder project. In a few limited cases, we found design problems or oversights that were not relevant to the smaller Pathfinder design, but could have been problematic for MER.

The tight schedule also caused a great deal of quality concern because the potential existed to shortcut the verification program to make it to the launch pad. A clear lesson from Mars '98 was that a strictly rigorous verification and validation program is a mandatory component of mission success. This is even more the case on a schedule constrained effort like MER, because a robust test program is the last line of defense for a rapid design & development effort. To achieve this robustness, the project dedicated significant resources (personnel, hardware, budget) to the test program. In addition to the two flight spacecraft, a total of four flight-like testbeds were developed and used for V&V. A very comprehensive environmental test program was conducted involving nearly 30 separate system level tests (solar thermal vac, launch dynamics, landing dynamics, EMC, etc.). A large test team was assembled from the design & development staff to insure adequate cradle-to-grave knowledge.

The content of the test program was managed using a very detailed incompressible test list (ITL). Standard JPL practice is to define at a high level the set of mandatory tests which need to be performed on the flight spacecraft prior to launch. Because of the MER schedule pressure, the project and institution decided to greatly expand the level of detail in the ITL and formalize the process for managing the list. The scope of the list was also increased to include verification efforts that did not occur on the flight vehicle. This was particularly important given the criticality of the testbed effort in verifying flight software functionality. The ITL was generated before the start of the verification program and was formally agreed to by both JPL and laboratory management. A small number of waivers to the list were approved during the execution of the test program, but the vast majority of the tests were executed as planned. For each waiver, independent technical analysis was performed to assess the risk prior to institutional approval.

TRANSPARENCY

The obvious challenges and importance of the MER Project to both NASA and JPL meant that the project was always under a great deal of internal and external scrutiny. This was a marked difference from the Faster-Better-Cheaper era, when adoption of a "skunkworks" approach was standard. Managing the impact of this greater level of oversight was a significant challenge to the project leadership team. The project's approach to this effort was to develop and maintain an extremely open and transparent relationship with the science team and NASA/JPL management. This transparency requires overhead in terms of communications and interactions, but also creates a trusting environment. This trust was critical during the periods when the project's technical and programmatic challenges appeared insurmountable. Fortunately, both the science team and higher level management developed a strong belief in the team's ability to resolve issues – and this confidence turned out to be well founded.

TECHNICAL CHALLENGES

The project faced a number of technical challenges in addition to the previously discussed programmatic issues. Many of the technical issues were related to mass and the early disconnect between EDL system capabilities and rover needs. The project developed a new EDL system, and managing the mass of that effort turned out to be a significant effort. A weekly mass council was conducted through most of the development effort to assess the mass status, identify growth areas, exercise descope options and trade resources (budget, schedule, mass, volume). As previously mentioned, the limited mass margin forced the project to optimize the design of many components. Many structural elements were fabricated using composite materials, and the project faced a number of difficult challenges designing and building complex composite structures with many difficult interfaces.

Another significant challenge faced by MER was the difficulty in getting the rover off the lander onto the surface of Mars. This problem was not really addressed by Mars Pathfinder because the lander contained most of the mission functionality (the Sojourner rover effort solved the egress problem at a much reduced scale). The challenge of driving a 400 kg rover over a tilted lander platform 40-50 cm off the ground was not identified as a major concern early on. Eventually, however, it became apparent that this problem would drive the rover's mobility capability beyond what was required to drive on Mars. This problem is aggravated by the presence of the deflated airbags below the lander petals. To mitigate this issue, a set of special egress ramps were added to the design to aid the rover during the egress activity. Nevertheless, the challenges seen during the first few days of the mission (particularly on Spirit) showed that the design architecture made this problem a major challenge.

KEY LESSONS LEARNED

The major lessons learned on the MER project are mostly reflected in the challenges described above. The early history of the project demonstrates how important it is to have an adequate program formulation effort. The lack of alignment between the project team and program office on the project's development paradigm (science driven vs. capability/cost driven) could have been rectified with a longer formulation period.

The same is true of the disconnect between the capabilities of the inherited EDL system and the rover's needs. A longer and more complete formulation effort would have resulted in a better understanding of the baseline schedule and budget, and would undoubtedly reduce both the budget overrun and schedule slip. Of course, it was not really possible to implement this lesson on MER due to the short time between project start (May 2000) and launch (June 2003).

> Lesson: Provide for an adequate program formulation period to ensure that appropriate alignment occurs between project paradigm, science objectives, technical margins, and heritage assumptions.

Although challenging in some respects, the effort to build and fly two vehicles was extremely valuable. The value of a dual mission from a mission risk/return perspective is obvious. The project was able to leverage the investment in the design/build effort to both reduce the landing risk and increase the science return. The two missions also decreases the science risk because it allowed us to go to two scientifically diverse sites. The value of a dual mission from a development risk is not as easily assessed, but our experience is that it is equally important. It was certainly difficult to develop, build and test both flight units, but the advantage in terms of hardware richness was worth it. The combination of the two flight vehicles and four testbeds meant that the project could perform a very strong test program. By spreading V&V efforts through all available venues, we greatly exceeded what would have been possible on a single vehicle. This improved opportunity for testing undoubtedly led to discovering more problems and improving the overall quality of the product. This outweighed the logistical difficulties of getting all the hardware built.

> Lesson: Adopt a hardware rich development effort though multiple flight units or testbeds. Manage the logistical difficulties in producing this hardware, and make maximum use of this extra hardware in a robust test program.

A number of factors contributed to the success of the MER mission. Of these, none was more important than the quality of the team. JPL put in place a strong and capable team at the beginning of the project, and brought in additional senior personnel when the project was faced with significant development challenges. The project adopted a cradle to grave staffing approach to ensure that the key design & development personnel stayed through test and flight operations. This approach meant that the project could retain important corporate heritage and eliminate inefficient (and risky) personnel transitions. The project also made a specific effort to obtain a good mix of experienced senior personnel and energetic newcomers.

> Lesson: Staff the project with a strong & diverse team and keep them from cradle to grave

MER extended the capabilities of the Mars Pathfinder EDL architecture, but also demonstrated that further expansion is somewhat problematic. The airbags had to be significantly upgraded to handle both the increased rover mass and the larger wind induced horizontal landing velocity. Further payload mass growth would be difficult to accommodate because the stroke capability is limited by the basic geometry of the airbag system. In addition, the volume inside the tetrahedron lander was quite limited, and forced the rover design to include a complex set of deployments. Adding more mass inside the lander would be very difficult because of the limited volume margin. Finally, the airbag architecture makes the task of rover egress much more complex. Future EDL systems should make sure that the task of safe landing includes getting the payload all of the way onto the surface of Mars.

> Lesson: Further extension of the Mars Pathfinder/MER EDL architecture is likely to be problematic. A new generation landing system should be developed to improve scalability and provide a robust approach to rover egress

SUMMARY

Despite the overall success of the Mars Exploration Rover missions, there were a number of challenges that made the project exceptionally difficult to implement. These problems include issues with the basic mission concept, a highly aggressive schedule, and a significantly modified Entry, Descent, and Landing system. Fortunately, these problems were successfully resolved and the mission was executed as planned. Nevertheless, a number of useful lessons were learned that should prove to be useful for both future Mars rover missions and general space exploration efforts.