# Systems Engineering the Mars Exploration Rovers

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## Abstract

The Mars Exploration Rover (MER) Project is one of the most complex robotic space exploration missions ever undertaken and went from concept to launch in a record time of three years. Although the mission has proven very successful, the compressed schedule, tightly integrated design inherited from the Mars Pathfinder mission combined with a new rover design presented a huge systems engineering challenge and MER's development was consider high risk. This paper will overview the project highlighting some of the systems engineering approaches used throughout the project lifecycle to address the challenges as well as lessons learned.

## Introduction

In the Spring of 2000, NASA's Mars Program (managed by the Jet Propulsion Laboratory) was facing many tough questions and choices. The very successful Mars Pathfinder Mission of 1997, with its small Sojourner rover, had renewed the vision for the scientific exploration of the Martian surface. However, the Mars missions which followed, Mars Climate Orbiter, Mars Polar Lander, and the 2 small Mars penetrator probes had all been lost upon arrival at Mars in late 1999. There are inherent risks in any space mission, and the odds of successfully reaching Mars are <40% (based on all international attempts). NASA's Mars program had plans to make use of every opportunity (approximately every 26 months when Mars and Earth are close in their orbits) to launch new spacecraft including orbiters for global remote sensing as well as lander and rovers for in-situ surface exploration. But given the science objectives, resources available and risks, was this the right strategy? In early 2000, the Mars 2001 Orbiter (named Odyssey after launch) was on track for its launch in April of 2001 and the question was what if anything could be launched in the 2003 opportunity. Mars would have its closest approach to Earth in over 60,000 years in 2003, which equated to getting more mass there for the same energy. Mission studies for larger more capable science rover had been done but with only three years until launch, was there enough time to design, build and test such a mission? With little time to decide, the concept of using as much heritage as possible from the successful Mars Pathfinder Cruise and Entry Decent and Landing (EDL) systems with a larger rover as payload was selected from several options and the Mars Exploration Rover Project was born. Within three months, the desire to maximize science return and minimize risk of failure at Mars had raised the stakes to building, launching and operating two identical spacecraft for the 2003 opportunity.

## Mission Overview (Level 1 requirements)

The MER mission consisted of four distinct phases: 1) Launch 2) Interplanetary cruise, 3) Entry Descent and Landing (EDL), and 4) Surface/Science operations. (Although Launch and insertion of the spacecraft on its Mars trajectory are a set of critical events, they will not be discussed further here.) Using a minimum energy trajectory, it took approximately 6 month for each of the MER spacecrafts to travel over 300 million miles and arrive at Mars. Like the Mars Pathfinder mission in 1997, there is no orbital phase at Mars. The EDL systems is a direct insertion, decelerating from over 12000mph to 0 in less than 6 minutes using an aeroshell and atmospheric friction, a parachute, retro rockets and finally airbags to cushion the surface impact. The EDL phase was one of the most complex as the systems needs to morph from a cruise configuration to a lander and any error would have almost certainly lead to the loss of the mission. Once on the surface, the system again had to transform itself from lander to rover and then begin the purpose of its journey, to understand the geologic history of Mars.

The science instruments selected for the mission include both remote sensing as well as in-situ components. For remote sensing a pointable mast assembly includes:

- Panoramic Cameras (Pancams) – a stereo pair of 1Mpixel cameras with changeable bandpass filters to gather spectra information in visual range (and create color images)
- Miniature Thermal Emission Spectrometer (MiniTES) – a point spectrometer in mid-infrared enabling remote analysis of mineralogy. (The mast is actually an optical periscope for this instrument, which needed to be mounted within thermally controlled body of the rover.)

For in-situ investigation, a 5-degree of freedom robotic arm enables precision placement of 4 devices on rock and soil targets:

- Rock Abrasion Tool (RAT) – a small grinding device to remove up to 1cm of rock surfaces
- Microscopic Imager (MI) – a 1Mpixel close-up imager
- Alpha Particle X-ray spectrometer (APXS) – a spectrometer for determination of elemental composition of surface material
- Mössbauer Spectrometer (MB) – a spectrometer for determination of Iron mineralogy of surface material

The Level 1 requirements (negotiated between NASA HQ and JPL which manages the mission) primarily address the opportunity and required science to be accomplished by the mission. In summary these are:

- Launch 2 identical rovers to Mars in the 2003 mission opportunity.
- Land on Mars within a latitude band of 5N to 15S (MERA) and within a latitude band of 10N to 10S (MERB).
- The spacecraft shall approach Mars on a trajectory designed to support communications with Earth during EDL through roll stop. The spacecraft shall

provide direct communication of data during EDL through roll stop at a rate and volume sufficient to provide for fault reconstruction.
- After successful landing, provide vehicle performance data of the entry, descent and landing operations.
- The rovers shall each acquire science data and conduct in-situ analysis for 90 sols.
- The rovers shall be designed to utilize direct-to-Earth X-band communications for surface operations and utilize 2-way UHF communications through the Mars 2001 Orbiter as an operational capability.
- At each landing site operate the following science package: the remote sensing instruments: the Panoramic camera stereo/color imager (Pancam), and the miniature thermal emission spectrometer (mini-TES); and the in situ instruments: the Alpha Particle X-ray Spectrometer (APXS), the Mössbauer spectrometer, the microscopic imager and the rock abrasion tool (RAT). The science package also includes a magnet array and calibration targets for the instruments.
- At each landing site acquire: at least one full color and one stereo panoramic image of the site with the Pancam; at least one image of freshly exposed Mars rock that is also analyzed by another instrument; color and hyperspectral mid-IR panorama images.
- Drive the rovers to a total of at least 8 separate locations and use the instrument suite to investigate the context and diversity of the Mars geologic environment.

In additional there are several requirements intended to demonstrate capabilities for future missions:
- Operate both rover missions for at least 30 sols simultaneously on the surface of Mars.
- Demonstrate telecommunications capabilities through the Mars Express orbiter.
- At least one rover shall demonstrate a total traverse path length of at least 600m with a goal of 1000m.

## Systems Engineering Approach

Figure 1 – Project Lifecycle

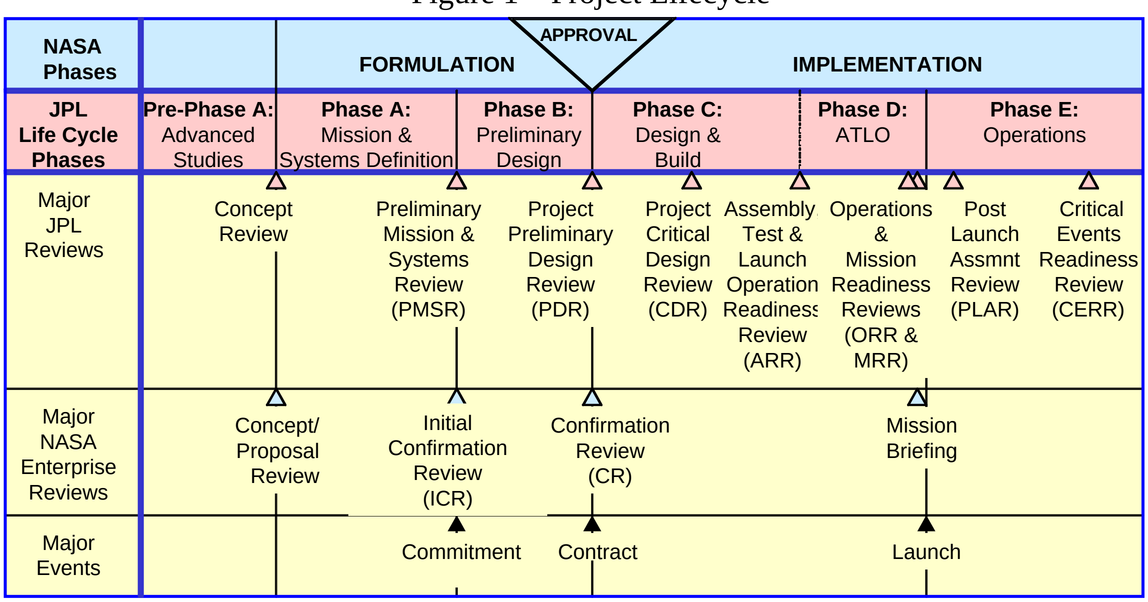


Figure 1 shows the typical project lifecycle for JPL robotic space missions. The spacing is the rough portioning of schedule to the different project phases. However, given a three-year from concept to launch schedule for MER, the formulation phase needed to be compressed. The time from Concept Review to Preliminary Design Review was given less than six month in order to ensure the hardware and software design, build, test cycle had as much time as possible. A major challenge was therefore how to get all the required systems engineering work (requirements, interface definition, design trades, etc.) done in this short formulation phase.

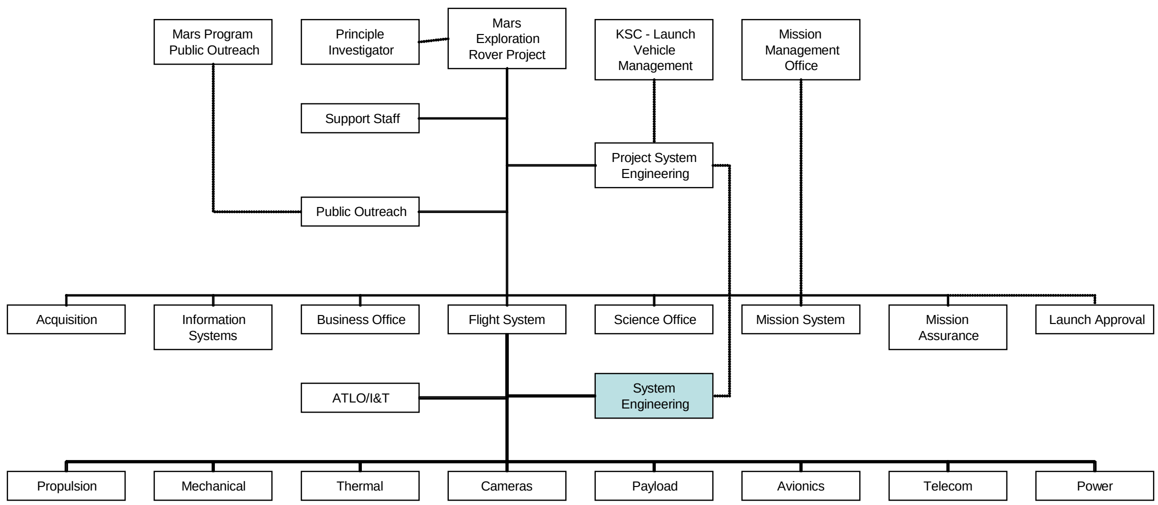



Figure 2 - Project Structure

MER had a project hierarchy as shown in Figure 2. The flight system, the organization responsible for the design, fabrication, and testing of spacecraft, was the largest organization and contained subsystems based on engineering discipline (mechanical, thermal, telecommunication, software, power, etc.) as well as the flight systems engineering organization. (This paper focuses on the systems engineering specifically for the flight systems. There were of course additional systems engineering activities within mission operations and other areas.) MER was performed as JPL 'in house' project; that is, all the major systems engineering functions were done at JPL with select subsystems/components being contracted to industrial partners. By the time of launch, over 50 work years of effort had gone into systems engineering the spacecraft.

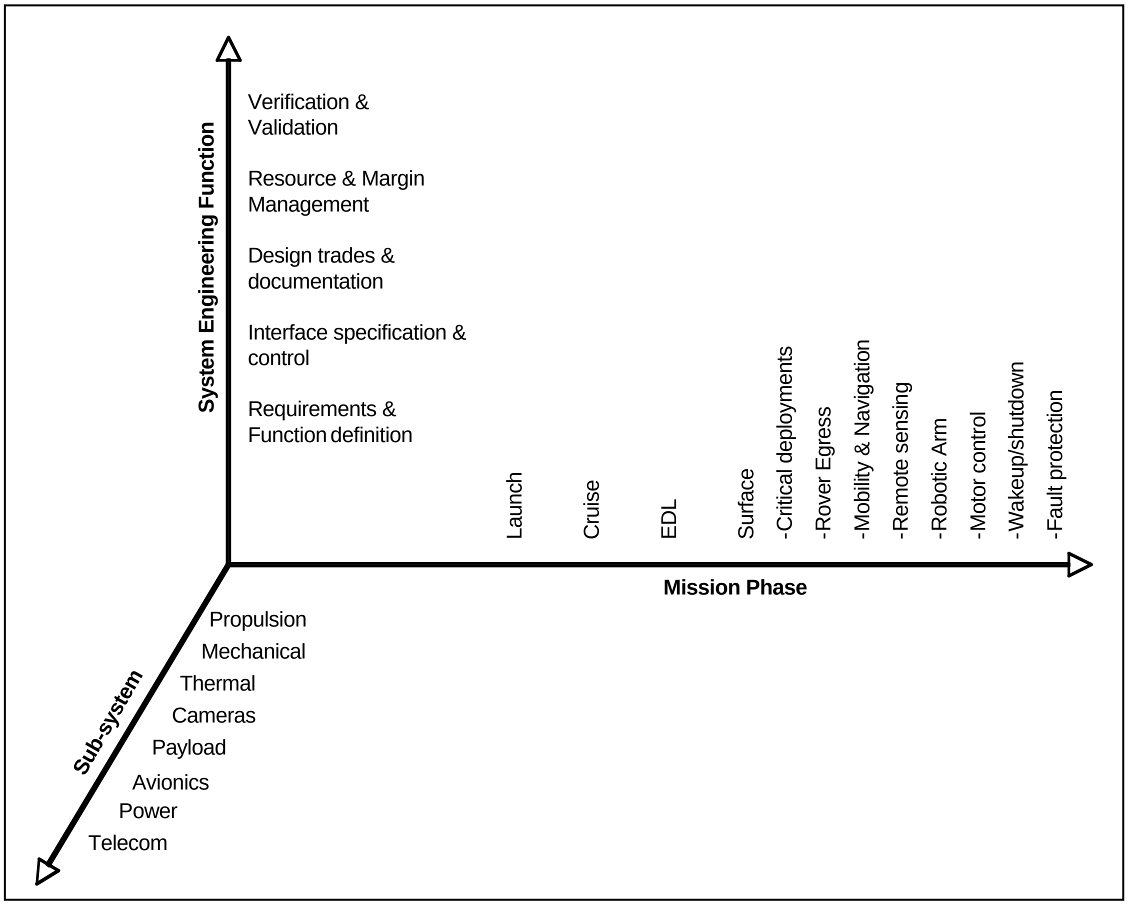
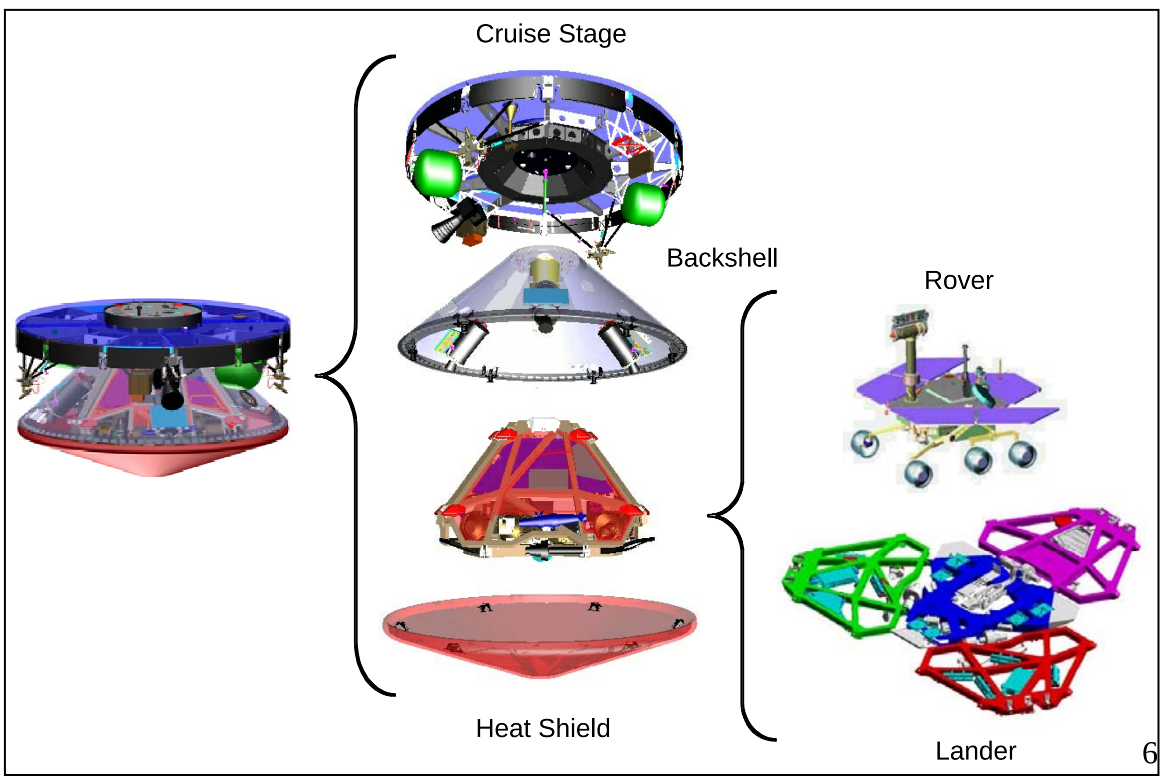



Figure 3 – Systems Engineering Space

Systems engineering is a multi-dimensional activity and can be looked at many different ways. [1] Figure 3 illustrates one way of how systems engineering functions (e.g., requirement definition) needs to be done both in terms of specific mission phases or activities (e.g., rover egress from lander) as well as across engineering subsystems or disciplines. For MER, an organization was needed to enable systems engineers to cover both the breath of the mission as well as penetrate into the depth of specific critical mission activities and all the involved engineering subsystems. It should be recognized that MER was essentially three different missions in one: cruise, EDL, and surface. Each has very different requirements leading to different mechanical configuration, different sensors, different software, etc. Due to the complexity of each phase as well as the interconnections and transition between them, no single systems engineer could cover the breath and depth of the entire mission. Systems engineering deliverables (requirement documents, subsystems interface specification, etc.) were broken down into those that were contained within one mission phase (i.e., EDL) and those that were crosscutting. Systems engineering leads were assigned in both areas. For instance a systems engineer was assigned to define, document and get concurrence on all the coordinate frames, alignments, pointing and phasing conventions through all mission phases to ensure continuity. Another systems engineering lead was assigned to work only the rover's robotic arm area covering the depth of its complex interfaces across all subsystems. In both cases, the Systems Engineer's role was to assemble and lead a team of representatives from all the effects subsystems to complete the necessary engineering activities.

The role of a systems engineer changes overtime as the project moves from formulation to implementation to operations phase. A key systems engineering function during the formulation phase is to develop, document and get commitment to requirements and interfaces as well as develop and analyze a preliminary design to meet the requirements. Initially on MER, much of the systems engineering staff was assigned either to a specific systems engineering functions (i.e., requirements definition) or a specific subsystems (e.g., power). The staff was brought together (with representatives from other organizations) in a design team to work and resolve issues. However it quickly became obvious that this process was not going to meet the compressed timeline to get to PDR. Several systems engineers were therefore reassigned as leaders of functional areas or mission activities (e.g. rover mobility) working all the systems engineering functions and across all the engineering disciplines within that area. In time, the majority of systems engineers became specialists focused on a specific mission-level activity addressing all systems engineering issues associated with it. This approach kept mission objectives in the forefront, enabled faster convergence on requirements and interfaces, and identified trouble spots early. It also allowed decisions that were completely within a specific mission phase to be made more quickly then if a room full of systems engineers each representing a traditional engineering discipline had to be convened for each decision. There were of course several areas where it continued to make sense to have systems engineer dedicated to a specific functions or discipline. An example of this is the electrical interfaces and interconnections, which were very complicated and needed the attention of a dedicated systems engineer.



## Flight System Design

Figure 4 – MER Spacecraft configuration

In order to illustrate some of the systems engineering challenges a brief overview of the spacecraft design is provided here. Figure 4 shows the “Russian Doll” configuration of the spacecraft inherited from Mars Pathfinder design. At the heart of the system is the rover and science payload to be delivered to the surface of Mars. The rover was a new design inheriting some of it design concepts from the Sojourner rover but scaled up to carry the larger science payload and meet the mobility objectives of the mission. The rover contains the flight computer that is used to control the spacecraft in all of the mission phases. The computer is a 32bit processor running at 20Mhz of the same design used for the Mars Pathfinder mission. The rover is all solar powered (limiting it to equatorial landing sites) and included rechargeable batteries enabling nighttime and high power operations. The energy budget only allowed the rover to be awake about 6 hours each Martian day. (The Martian Solar day, or Sol, is 39 minutes longer than an Earth day.) The rover communication system includes a direct to Earth X-Band transceiver (also used in cruise) as well as a UHF transceiver for communication with mars orbiters for data relay to Earth. The six wheel “rocker-bogie” mobility system included steering on the four corner wheels and enabled traversing over a variety of terrain at speeds up to ~150meters/hour (~0.1 mph).

The rover is stowed in the tetrahedron lander, which designed to be self-righting when the side ‘petals’ open on Mars. The lander is encases in airbags (not shown in figure 4) that are inflated just before touchdown to absorb the impact. Even with the airbags, the system needed to be designed to withstand landing loads of over 50 Gs. The lander is housed within a blunt nosed aero-entry vehicle with conical backshell and heat shield for atmospheric entry and deceleration. The entry vehicle is attached to the circular cruise stage, which contains the propulsion systems and attitude control system for interplanetary travel. The cruise system is spin stabilized at 2rpm during interplanetary cruise using momentum to maintain attitude control minimizing ground interaction and need for on-board closed loop control.

Although the tight coupling and nested nature of the design looks elegant, it is also unforgiving. That is, any small change in hardware shape or size is likely to cause other design changes. Moreover the transformations that must take place between the different mission phases require a host of special design features. Each piece had special sensors or actuates that had to communicate eventual back to the flight computer in the rover. Developing and managing the electrical inter-connection alone and how they would be safely separated at different points of mission was terribly complex. As the preliminary design progressed it was realized that much of the Mars Pathfinder design would have to be redone to meet the specific requirements of the MER mission. The landed mass with large rover and science payload was 50% over Pathfinder, which required a redesigned lander structure, parachute and airbags to make EDL work. But MER had to maintain the overall size the spacecraft the same as Pathfinder to fit within the launch vehicle constraints.

## Systems Engineering Lessons Learned

MER's biggest challenge was schedule, and in particular for systems engineering the shortened formulation phase. Some of the assumptions in the ability to inherited parts of Pathfinder design proved false after PDR once the MER mission specific applications were analyzed in detail. Therefore the biggest lesson learned is to ensure an adequate formulation phase. The following are additional lessons related to specific systems engineering functions.

Requirements & Interfaces

A rigorous iterative process of requirements definition and interfaces could not be done within the available schedule. The results were that the detail of requirements varied widely and verbatim flow down of some requirements took place due to lack of time to iterate meaningful decomposition. Although interface documents were released they often went through significant change during the implementation phase as more about the design was learned leading the late design changes. Additional documentation to adequately describe the complex behavior and functions of the spacecraft was also needed. Detailed Functional Design Documents/Descriptions (FDDs) were developed by systems engineers to define systems level functionality and became requirement documents for flight software. For example, one FDD covered the rover wakeup and shutdown behavior. These helped to correct some of the shortcoming of the traditional requirements and meshed well with systems engineers being assigned to specific mission functions or activities as they could take ownership of document.

Baseline Design

The compressed schedule meant the design was in a constant state of change. "What is the baseline" became a common phrase. The complexity of design and limited schedule made it impossible to capture the design in any one form or by any one person. The electronic library used by the project help in making information available through the project but the sheer volume of information could make finding what you needed a daunting task. Design changes went through a formal engineering change request/approval process but often there was inadequate time to evaluate all possible impacts before needing to commit to changes. Impact on testing/retest was sometimes not fully realized at the time the change was approved. Extra effort was also put in to making a tightly integrated design to 'save' resources (e.g., use same flight computer for cruise, EDL, surface) but this had other costs. Seemingly small interface changes rippled through entire systems. Systems testing became difficult because of the level of integration often needed what seemed like unrelated parts to be plugged together. Because of the potential short life of the rovers (90 sols), additional capability/functions were often justified in name of operability even though they were not directly traceable to requirements. These additional capabilities, although enhancing to the mission, required not only implementation but often impacted the schedule more significantly during testing.

Verification &Validation

The verification and validation (V&V) program is critical to prove the integrity of the design and the ability to perform mission functions. One of the first steps was to map the requirements to verification items. This was difficult as the requirements themselves were not rigorously developed and a variety of documentation defining the systems had to be culled through to fully identify a database of testable items. Although this database was necessary, the review of the detail test procedures and results became key in ensuring the right V&V was done. Again, having a systems lead for important functional area that followed the process from requirements, through implementation, and then into test was key to ensuring quality of the product. There was concern on the need for "independent testing" rather than relaying sole on systems engineer who originally helped to conceive the design. Dedicated test engineers could formulate objective tests but they couldn't replace knowledge/experience of systems leads. A teaming relationship between test engineers and systems engineers helped ensure a complete and through V&V program.

Organization

Personnel who can take ownership of key functional areas "cradle to grave" (including operations) worked well for MER. The project assigning systems leads based on mission phases or activity to see those through from requirements, implementation, test, and often into operations. This organization was not laid out at beginning of project and therefore not clearly aligned/integrated with management structure. Systems leads needed authority to direct technical activities but were not directly responsible for cost. Again, the short formulation phase did not allow time to fully develop & understand roles for systems engineers and relationships to other project elements.

## Summary

The Mars Exploration Rovers have proven to be one of the most successful interplanetary space missions to date – although that success was never guaranteed. The complexity of the design and the tight schedule made effective systems engineering even more critical. To ensure requirements and interfaces were met and enable rapid decision making, systems engineers took on lead roles based on mission phase activities versus engineering discipline. This was a cradle to grave approach where the systems engineer provided technical leadership of a specific activity from requirements definition, hardware and software development, subsystems and systems test/verification and in many cases into operations. Although this approach helped MER meet its tight schedule, of perhaps more importance was the sheer dedication and effort the team applied to meeting what at some points seemed like an impossible task. It is recommended that future projects explore the MER systems engineering approach for applicability to their mission with understanding that it is not mitigation for an inadequate formulation phase.

## References

1. Space Mission Analysis And Design, Third Edition, James R. Wertz and Wiley J. Larson (editors), Space Technology Library, Microcosm Press, 1999.