Verification and Validation of Mars Exploration Rover Surface Capabilities

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Abstract *- This paper will discuss the system level verification and validation test program for the surface capability of the Mars Exploration Rovers (MER). The Mars Exploration Rover project was on an extremely challenging schedule of going from concept to launch in just three years. Although the cruise and entry, descent and landing (EDL) systems were based on the successful Mars Pathfinder mission of 1997, the MER rovers and their sophisticated science payload were a new development and the expectation for the surface capability were very high. The rover hardware and software were developed to allow certain functions to work in parallel to maximize the science that could be done each day on Mars. However this lead to complex behavioral interactions which had to be tested and verified before they could be used. An incremental test program was developed that first exercised and verified individual functions and then validated system capabilities in mission-like scenarios. The plans, execution and results of these mission-like surface system tests will be presented.*

Keywords: Mars, Rovers, Verification, Validation, Testing.

1 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 two 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. A major challenge was not just to design and build the spacecraft but also provide adequate testing to ensure the complex surface science mission would be a success.

2 Mission Overview

The MER missions consisted of four distinct phases: 1) Launch 2) Interplanetary cruise, 3) Entry, Descent and Landing (EDL), and 4) Surface/Science operations. 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 for atmospheric deceleration, 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 gather data to understand the geologic history of Mars.

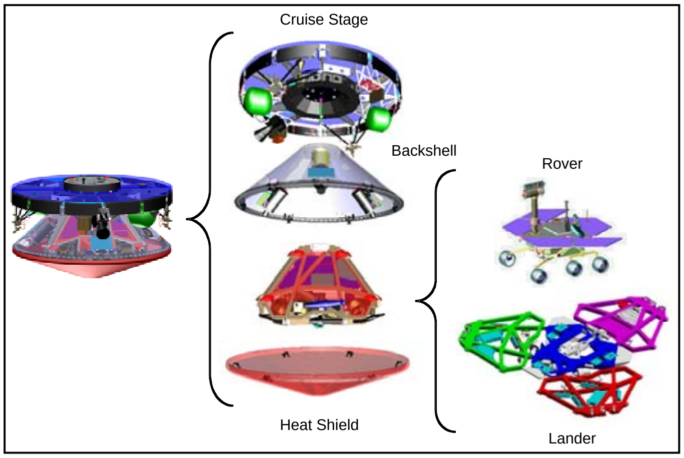

Figure 1 – Flight System Configuration

Figure 1 shows the "Russian Doll" MER spacecraft configuration inherited from the 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 is designed to be self-righting when the side 'petals' open on Mars. The lander is encased in airbags (not shown in figure 1) that are inflated just before touchdown to absorb the impact. 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.

The surface mission (once the rover had safely completed it checkout and deployment from the lander) was essentially to use the rover and its scientific instrument suite to work as a robotic field geologist. 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 band pass 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 (termed the instrument deployment device or IDD) 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 rover also includes 6 engineering cameras. Mounted on the mast with the Pancams are a stereo pair of navigation cameras (Navcams) to acquire images for ground operators plan rover traverses. On the fount and rear of the rover body are stereo camera pairs (Hazcams) used by autonomous navigation software on-board the rover to identify hazards.

The science and engineering teams work together each day to plan the next Sols operations based on the outcome of previous activities. The surface mission was envisioned to have prototypical Sols of whose primary objective fell into one of the following four types:

- Remote sensing – Mars day focused on acquiring imaging and miniTES spectrums
- Drive – long traverse towards some target of interest
- Approach – final approach and position at target for in-situ investigation
- IDD Sol – use of IDD and its instruments for in-situ investigation.

The detailed operations on any Sol would be controlled by the command sequences generated by the operations team. However, the rover was designed to have a variety of automatic and autonomous functions in order to maximize the operability of the surface system. This included high level commands or behaviors, such as autonomous navigation, that minimize the number of commands the operations team need to achieve the desired goal. The flight software also included activity constraint management and resource arbitration. For instance, the rover contained over 30 electric motors but had only 12 motor controllers which were muxed between the motors limiting what actuations could be done in parallel. Therefore certain activities could be done at the same time, such as imaging with mast mounted cameras and use of IDD, while other things, such as driving and moving high gain antenna, could not. A behavior relationship matrix was developed to identify conflicts and how they should be addressed. A traditional approach to resolving unanticipated conflicts is to have the spacecraft immediately go into an idle 'safe' mode and wait for the ground to resolve the problem. However, given the 90 Sol primary mission life and science objectives, there was a need to enable the rover to continue to make progress and do the higher priority activity in the face of a conflict. A key part of the surface system verification program was proving that rover would indeed manage the behavior interactions correctly.

Two high-level behaviors that provide vital infrastructure for surface functionality were the vehicle wakeup and shutdown behavior and the communication behavior. As noted previously, the solar power rover could only support ~6 hours of computer on time per Sol. The rover would typically shutdown and wakeup up several time during the day and night depending on the science objectives. The communication behavior enabled an automatic table driven approach to defining and executing communications with Earth as well as Mars orbiting assets. Intimately built into both these behaviors were fault protection modes to ensure the power/thermal safety of the vehicle (e.g. does not stay awake to long) as well as ensure the ground does not lose communication with the vehicle.

3 Surface System Verification and Validation Approach

The overall MER Verification and Validation (V&V) plan included: 1) subsystem functional verification, 2) environmental verification at subsystem and system level, 3) system functional V&V and 4) Operational V&V. This paper focused on the third aspect, system functional V&V specifically for the surface system or science portion of the mission. At this point in the test program, the individual subsystems (e.g. cameras) have been shown to work but we need to validate that rover could execute a typical Sol's worth of science and engineering activities including infrastructure activities (wakeup/shutdown, communication) and parallel activities. Operational tests which demonstrated end-to-end mission operations including ground tools, processes and teams are done but assumed the rover performance has already been proven.

The overall V&V process was managed through a database of verification items derived from requirements. This was hierarchical in nature following from subsystem test to system test to project level operational tests. Testing at the system level was typically organized around specific mission functions such as use of robotic arm, mobility or remote sensing. The verification items were further culled into an incompressible test list - a set of tests that had to be successfully completed in order to launch.

System level V&V for all critical mission functions is required to be done on the actual flight hardware. Testbeds are a vital part of the development and test program including post-launch and operations. (In fact all of the system level tests were developed and dry-run on the testbeds before run on the flight article to minimize test errors.) Because of testbed fidelity concerns, the goal is to test not just critical items, but all functionality on the flight system before launch. This is easier said then done as system testing must be coordinated within the overall assembly, test and launch operations (ATLO) schedule. Another important consideration was the level of flight software capability and maturity that would be in available at the time of a test. The flight software was developed basically in order of mission activities leaving key elements of surface functionality until last. (In the case of MER, a limited amount of higher-level surface capability was developed and tested post-launch and uploaded to spacecraft before landing on Mars.) This further constrained the system test schedule. Doing a test early would not have full flight software capability and therefore limit value of test. Pushing system test closer to launch made it more difficult to coordinate the necessary test configuration and duration.

4 Test Plans and Results

The approach for surface system testing was to, as much as possible, simulate prototypical Sols using flight like command sequences exercising full surface capabilities. This included :

- Infrastructure capability of vehicle wakeup/shutdown and communication behavior.
- Hierarchical sequenced control of activities including parallel activities. (Most of the ATLO functional testing was done by manually sending individual commands.)
- Exercise of remote sensing, robotic arm, and mobility functions in a flight like pattern.

- Exercise key system level fault protection for power, thermal and communication problems.

The project test plan resulted in a surface system test on each rover early in 2003 before they were shipped to Kennedy Space Center (KSC), as well as a test at KSC before final integration and launch. The planned content and results for each surface system test are discussed in the following sections.

4.1 System Test ST3B.2

In January of 2003, the first surface system test, labeled ST3B.2, was executed on the MER-2 spacecraft. Two previous system tests (ST1 and ST2) had executed cruise and EDL functionality. Immediately before this first surface system test would be regression testing of cruise and EDL, as well as the first impact to egress (i.e., rover deployment) system test (ST3A). The results of these tests would leave the rover in a fully deployed mobile configuration ready to test surface functionality.

System test ST3B.2 was broken into two parts, the first was to exercise three Sols of operations including wakeup and shutdowns, communication windows, remote sensing, mobility, IDD operations and some behavioral interaction. The second part was to test specific system level fault protection monitors and response.

The results of this first surface system test were mixed. This was the first successful test of a sequence driven operational like surface mission scenario on a flight vehicle. However there were known software liens, which prevented testing some capability and also produced problem. Chiefly was an issue with software interface with flash file system that resulted in unacceptable delays during commanded shutdown breaking the test timeline at several points. (The shutdown process should only take a few minutes to ensure all activities have been gracefully stopped before powering off the computer.) There were also some computational performance issues identified. For instance, imaging could generate a backlog of image compression work, which causes next activity to be delayed and run slower then expected. The specific test objectives and results are discussed below.

It should also be noted that there was some 'unintentional' exercising of functionality during this test. Only limited manual solar power simulation could be done, but several wakeup/shutdown functions are tied directly to the measurement of incoming current. By not having a good simulation, the system actual shutdown or stayed awake at unplanned time interrupting the test. However those behaviors were exactly what the system was designed to do given the power input at the time and demonstrated the systems robustness to operator error.

4.1.1 Drive and Remote Sensing Sol (Sol X)

Figure 2 provides a graphical depiction of the Sol X activities intended to exercise mobility and remote sensing as well as infrastructure functionality. The scenario was built around a constraints of Sol 20 assuming the MER-A vehicle landing at the Gusev site. Setup and configuration of the vehicle so it thought it was on Mars at a specific time and place was an important part of the test. For instance this would validate that the X-band high gain antenna was appropriately pointed towards where Earth would be when the rover was on Mars.

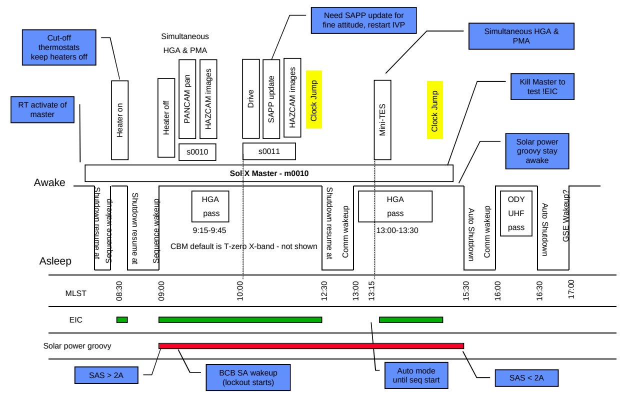

Figure 2 - Outline of Sol X

The sol scenario started with initiation of a master sequence which shutdown the vehicle and simulated sleeping overnight. This verified shutdown as well as wakeup at a specified time in morning using spacecraft alarm clock. The sequence then turned on warm-up heaters for high gain antenna gimbals and went back to sleep. Many of the rovers actuators and cameras required preheating for operations at the colder parts of the Martian day. After waking up and turning off the heaters, the sequence began a remote sensing sequences to gather Pancam and Hazcam imagery. In parallel the communication behavior autonomously started an X-band communication window demonstrating simultaneous operation of antenna gimbals and mast camera gimbals. After remote sensing and communication, the sequence went on to drive the rover a short distance, do an attitude update and end of drive imaging. A sequenced shutdown simulated a midday siesta to conserve energy. The rover then successfully woke-up to perform an X-band communication window and shortly thereafter the sequence resumed at a specified time. At this point a miniTES sequence ran successfully in parallel with communication window. An off-nominal condition to terminate the sequences was inserted at this point to verify the autonomous functionality of the shutdown behavior. The rover then automatically woke up for the afternoon UHF relay and then when back to sleep as planned.

4.1.2 IDD and Remote sensing Sol (Sol Y)

The second Sol of testing (setup for Sol 25 at Gusev) was focused on IDD and remote sensing activities. The day began with a solar array wakeup. This is a hardware function to ensure the rover wakeups each Sol should the alarm clock fail (or be miss-set). After this, a morning X-band high gain antenna window verified the autonomous communication behavior and actuation functionality in parallel to the IDD and RAT actuation. In the afternoon, the parallel operation of high gain antenna, IDD and Mast actuators was demonstrated

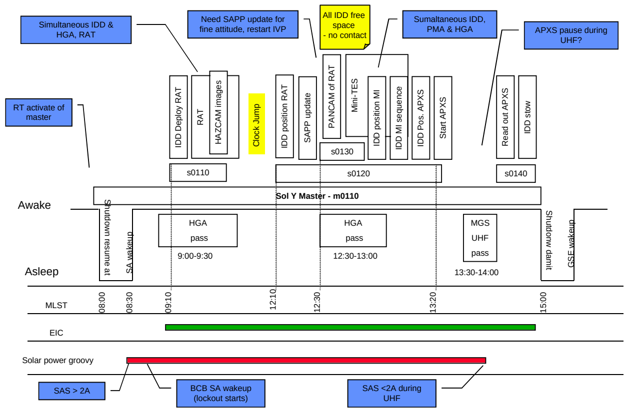

Figure 3 – Outline of Sol Y

4.1.3 Nighttime operations (Sol Z)

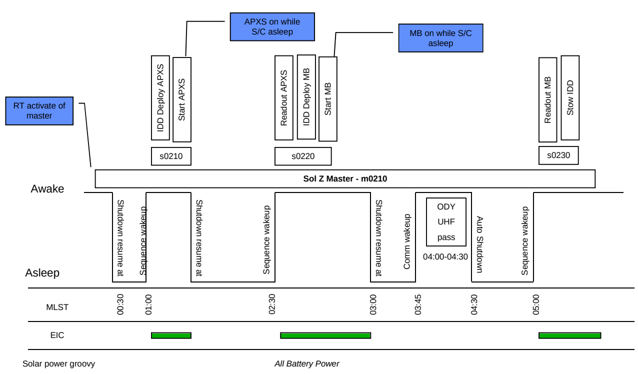

Figure 4 – Outline of Sol Z

The third Sol in the scenario was design to represent nighttime surface operations. This included a sequenced wakeup to deploy the IDD, place and start the APXS instrument followed by a commanded shutdown. A sequenced wakeup then commanded a tool change from APXS to MB and start its integration. The communication behavior did a wakeup for an early morning UHF relay followed by a shutdown. Finally, a commanded wakeup turned off the MB and stowed the IDD.

4.1.4 Fault Protection

System level fault protection included testing three key fault responses designed to keep rover stable in case of a thermal, power, or command loss problem. The rover power and thermal designs were deeply interwoven as the waste heat from the avionics inside the rover essentially provided needed thermal energy to keep them in operational range above the cold Martian temperatures. Mechanical thermostats connected to electrical survival heaters ensured that key component would not get too cold. However, running high power equipment such as X-band solid state power amplifier for prolonged periods of time (>4 hours) could raise the temperatures above allowable limits. A fault protection monitor using temperature sensors would trip an over temperature response, which would stop all sequenced activities, do a shutdown and wakeup for next planned communication window.

The second key fault protection test was the command loss functionality. Should a failure on the ground or onboard result in the rover not getting new commands for a specified period of time, the response onboard would be to try different communication configuration in a specific pattern enabling the ground to regain control.

The third area of system fault protection tested was low power. This indicated there was problem with rover batteries, which could occur while the rover was awake and software could take action or a low power event could happen while the rover was asleep. In either case the response was the stop ongoing activities and shed any non-essential loads and transition to special low-power operational state.

All of the system level fault protection monitors and responses were verified with the caveat that the shutdown delay problem with software and flash prevented some shutdowns from occurring in an acceptable time.

4.2 System Test ST3B.1

The goal of ST3B.1 was the repeat the same system tests described above on the MER-1 vehicle. However at this point in February we were less than one month until the MER-1 vehicle had to be shipped to Florida to prepare for launch. Critical environment testing still had to be completed. A window of opportunity was identified to perform the surface system test while the rover was going through vibration and shock testing. The idea being that most of the time of this environmental testing would be in setup and configuration where system functionality could be exercised.

In the end very little surface system testing was done and no V&V items were proven by this test. As the environmental test had priority is was impossible to run the as designed Sol scenarios within the limited time windows between vibration tests. Also the rover configuration was not fully deployed limiting what could be done. In part due to this inability to achieved test objectives, a system test 4 at KSC was planned for both MER-1 and MER-2

4.3 System Test ST4.2

System test ST4.2 took place in early March on the MER-2 spacecraft at KSC. Now with much more mature software that fixed the long shutdown problem, the goal was to repeat ST3.2B. However due to time constraints, only Sol X was exercised. This was a very good test with the one draw back that the rover was on a test stand and so mobility commands just spun the wheels in air. This test completed successfully verifying the two incompressible test items covering vehicle wakeup/shutdown and communication behavior.

4.4 System Test ST4.1

System test ST4.1 took place in early April on the MER-1 vehicle just 3 month prior to launch. The ST3B Sol scenario was collapsed in one mega-sol covering both day and night activities as shown in Figure 5 and 6.

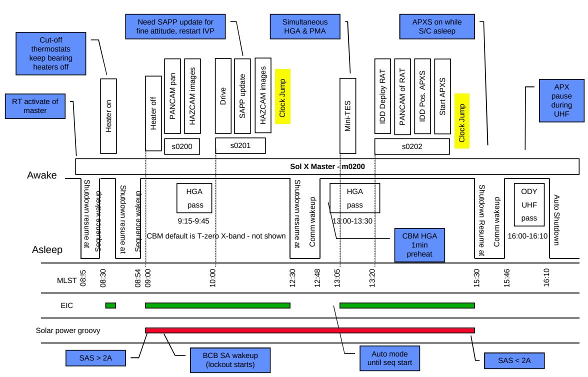

Figure 5 - Outline of Mega-Sol Day

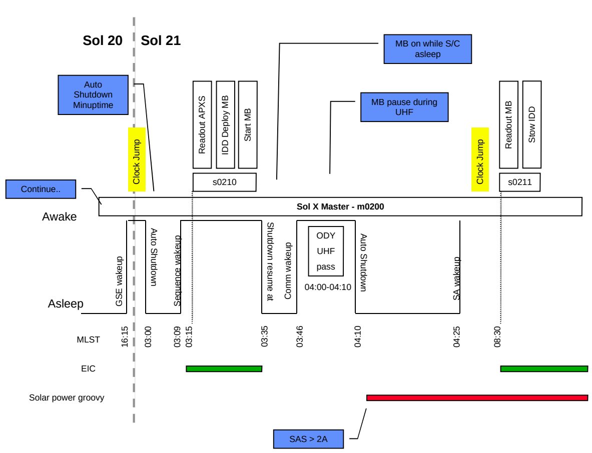

Figure 6 – Outline of Mega-Sol Night

The setup was also changed to use the Meridiani landing site for Sol 20. Like ST4.2, the rover, although fully deployed, was mounted on a test stand. The test ran very well and achieved verification of all critical items.

5 Summary

The MER surface system V&V effort focused on mission-like sequence driven operations. These were intended to exercise the infrastructure of the wakeup/shutdown, and communication behaviors in parallel to sequenced operations for remote sensing, mobility and IDD functions. In addition system level fault protection capabilities were tested. MER's biggest challenge was schedule which impacted both the time available for system test as well as the software maturity. The prototypical sol-like approach maximized the functionality of the test within the constraints. Although ST3B failed to fully verify key functionality, it did uncover system performance issue important to understand for successful operation. ST4 was able to compress the sol-like scenario approach and verify all key system level functionality before launch.

The research described in this paper was carried out at the Jet Propulsion Laboratory, California Institute of Technology, under a contract with the National Aeronautics and Space Administration.