MARS PATHFINDER SURFACE OPERATIONS VERIFICATION

Jennifer A. Harris
Jet Propulsion laboratory
4800 Oak Grove Drive
Pasadena, California 91109-8099
USA

ABSTRACT

Over 20 years have passed since NASA's Viking landers traveled to the surface of Mars. But now NASA is returning, in fact, it's already on the way with one of NASA's "faster, better, cheaper" missions known as Mars Pathfinder. This mission was developed in 3 years for $171 million dollars and is focused on engineering, science, and technology objectives. The Pathfinder spacecraft was launched December 4, 1996 and is scheduled to arrive on the surface of Mars during the Martian morning on July 4, 1997.

One of the many challenging aspects of the Pathfinder mission is strategizing, designing, testing), and verifying the engineering events of the first few days on the surface that will enable the science. of the mission to be carried out. Downlink of the critical Entry, Descent and landing (EDL) data, determination of the lander's orientation, and imaging of the lander and it's surroundings must all bc done early and accurately during the first Martian day (Sol 1). This will enable activities such as deploying the rover ramps, standing up the rover, pointing the High Gain Antenna (HGA) at earth, and finally driving the rover down the ramp for it's first traverse across the Martian surface.

in order to verify the end-to-end workings of the Pathfinder mission, an extensive end-to-end system has been assembled in JPL's Flight System Testbed for Mars Pathfinder (FST/P). This system includes a full-scale lander (with the Imager for Mars Pathfinder (IMP) camera and HGA), rover, and Attitude and Information Management (Al M) subsystem all located in a mom with sand, rocks, colors and lighting that simulate the Martian surface. Surface operational scenarios continue to bc tested in this environment with operations personnel participating in these tests making real-time decisions and assessments of the data in a flight-like environment. Determination and verification of key contingencies including low gain antenna (LGA) and no battery mission scenarios is also a large part of the surface operat ions val idat ion process.

Now, less than five months before arrival on the surface of Mars, there is still much surface operations testing to be done. With a possible surface mission of up to a year, the opportunities and challenges of surface operations design, test, and verification are immense. The reward, however, is great as we will all see on July 4 of this year as together we view Pathfinder's first image of Ares Valles, its Martian landing site.

MARS PATHFINDER OVERVIEW

The Pathfinder mission to Mars marks Americas return to the Martian surface after 21 years. Making extensive. use of technology and hardware developed for other interplanetary missions, Pathfinder accomplished it's development as a NASA Discovery mission. Under this classification, the development phase was limited to 3 years with a fixed cost of $171 M real year dollars ($1 50M in FY 1992 dollars). In the end, Pathfinder not only validated NASA's "faster, better, cheaper" way of doing business, it established a new and robust method of getting to the Martian surface.

Developed, built, and operated by the Jet Propulsion Laboratory in Pasadena, California, Mars Pathfinder was launched on December 4, 1996 aboard a McDonnell Douglas Delta II launch vehicle from the Air Force station in Cape Canaveral, Florida. A Payload Assist Module (PAM-D) upper stage sent Pathfinder out of Earth's orbit and on to Mars. Following a seven month cruise, Pathfinder safely arrived on the Martian surface on July 4, 1997.

Mars Pathfinder can be thought of as three individual spacecraft (figure 1); the cruise, entry, and landed vehicles. The main component of the cruise vehicle is the cruise stage. Responsible for gathering attitude data anti performing trajectory correction maneuvers during the seven month cruise phase of the mission, the cruise stage is jettisoned prior to entry into the Martian atmosphere. With the loss of this hardware, Pathfinder's shape becomes more like that of a typical entry vehicle. The heatshield and backshell protected the lander from the intense heal generated while passing through the atmosphere. The heatshield then dropped away, and the backshell housed the parachute and retro rockets that further slowed the lander's descent . Finally, the Pathfinder lander not only contains the airbags and petal motors that cushioned it's impact with the red planet and subsequently righted itself, it also houses the sole processor and all critical power and telecom hardware.

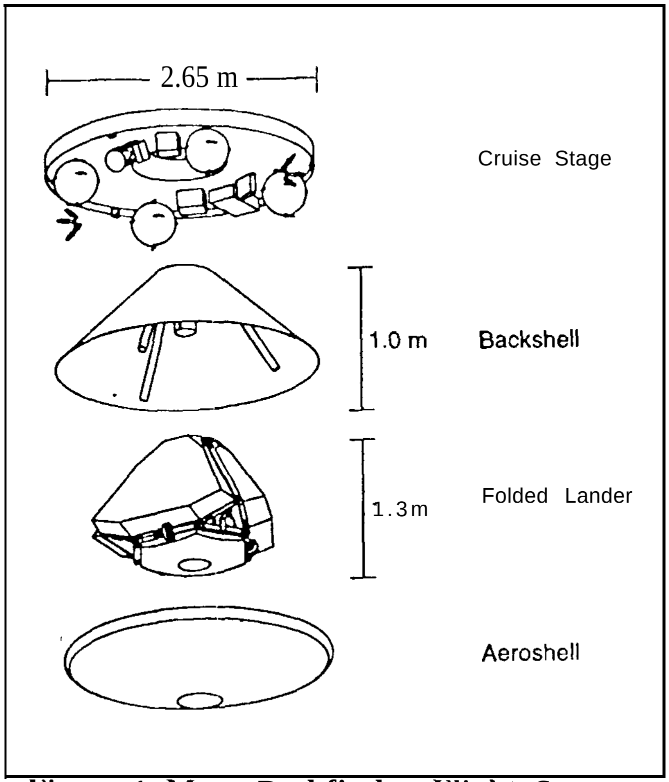

Figure 1. Mars Pathfinder Flight System

While the main objective of the Pathfinder mission was to develop a 'low cost delivery system to the Martian surface and return data gathered during the Martian descent, perhaps the most exciting part of the spacecraft was it's stowaway. Pathfinder delivered the Sojourner rover to the surf ace., and on the evening of their second day on Mars, the rover rolled down Pathfinder's ramps and became the first remote vehicle to set wheel on the Martian surface. Able to move around the landing site and perform numerous experiments, Sojourner also carried the A lpha, Proton, X-ray Spectrometer (AXPS) experiment that would allow scientists to determine the elemental compositions of various rocks. In addition to the rover, the Pathfinder lander carried 2 science experiments of it's own. The Imager for Mars Pathfinder (IMP) provides stereoscopic imaging of the landing site in addition to gathering spectral composition data by looking at the surroundings through one of 12 separate filters. The Atmospheric Science Instrument / Meteorology (ASI/MET) can collect pressure, temperature, and wind measurements on the surface after gathering acceleration, temperature and pressure data during Pathfinders descent to the Martian surface.

Located about 1000 km from the Viking 1 landing site, the Pathfinder mission touched down in the ancient outflow channel named Ares Valles. This site was scientifically attractive due to the possibility that a wide variety of rocks might have been deposited in the channel by a massive water flow that once raced through this area. The selected landing site has lived up to all expectations resulting in spectacular images, interesting rock samples, and challenging terrain to verify the rover's usefulness in future planetary exploration.

SURFACE OPERATIONS OVERVIEW

After Pathfinder's seven month cruise to Mars and it's Entry, Descent, and Landing (EDL) onto the surface of Mars, its surface operations mission began. As opposed to the autonomous EDL activities, Pathfinder surface operations required a significant amount of interaction from the ground operations team. The primary engineering objectives for the surface operations phase of the mission included; downlinking critical EDL data, assessing the lander health and tilt, deploying the ASIMET mast, deploying the rover ramps, driving the rover down a ramp, deploying the IMP camera head mast, and preparing the lander for semi-autonomous surface operations. Figure 2 shows the lander in it's surface operations configuration.

in addit ion 10a completely planned and tested mission for nominal conditions on the surface of Mars, several of the most likely contingency scenarios for adverse surface cond it ions were

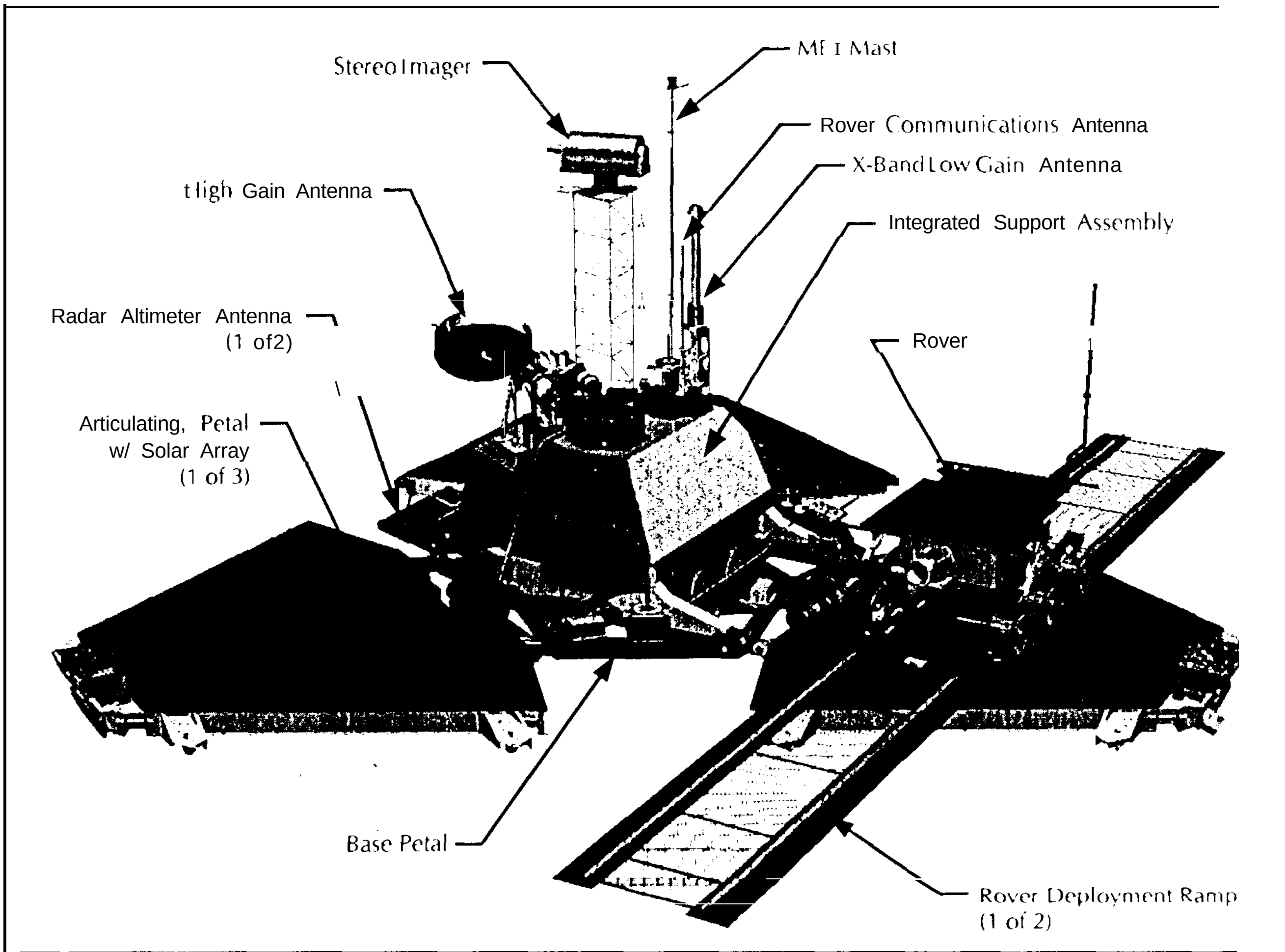

Figure 2: Mars Pathfinder Lander

developed and tested completely. This was necessary so that the operations team could quickly react to conditions on the surface that were different than those expected when designing the nominal mission. Figure 3 shows a set of the most likely possibilities for the flow of activities on the first day (Sol 1) of the surface mission. The nominal path is shown down the middle with the contingency paths shown being the low-gain antenna (LGA) , petal move, low power, additional imaging, and other off-nominal scenarios. The numbers in the boxes indicate sequence numbers associated with each step. In an effort to prepare for additional contingencies that couldn't be anticipated, the sequence architecture developed for early surface operations activities was highly modular. This allowed for the elimination and/or repeating of certain modules when necessary. in fact, it was a combination of the nominal plan and contingency plans that was the path taken on July 4, 1997 to accomplish the primary engineering objectives of the Pathfinder surface mission.

In addition to the flow chart describing possible contingency plans, a detailed procedure for sol 1 was developed throughout the testing phase of the mission. This procedure included the specific decision criteria necessary in order to determine which nominal or contingency path would be appropriate based on the data received at specific times during the first day on the surface.

SURFACE OPERATIONS TESTING OVERVIEW

The "faster, better, cheaper" philosophy of Mars Pathfinder development included an extremely rigorous test program. There were several independent testing environments that were used to verify flight software functionality, hardware /

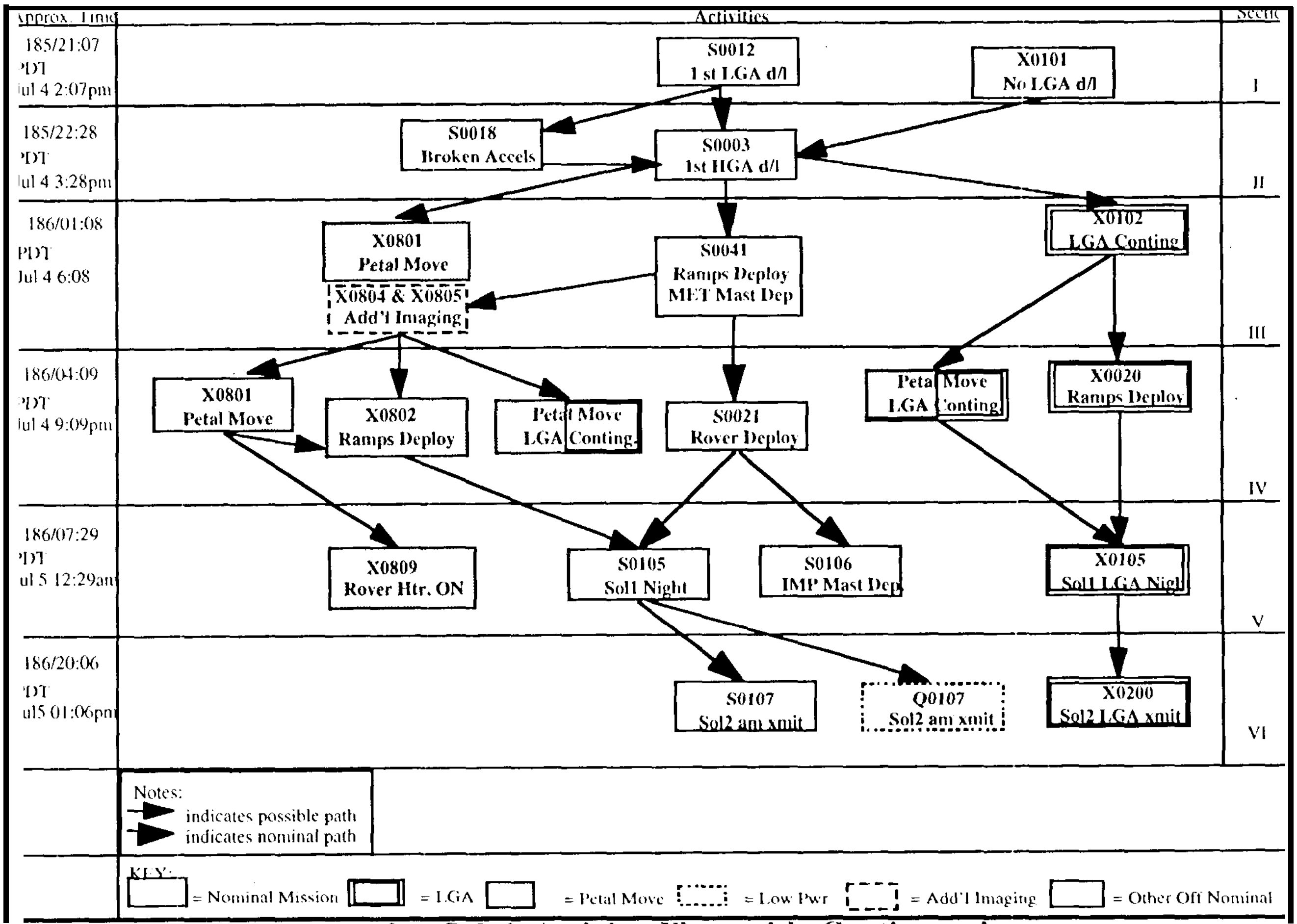

Figure 3: Sol 1 Activity Flow with Contingencies

software interaction, ground software, flight hardware functionality, and mission scenario feasibility. Pathfinder differed from many previous missions due to the rigor of its overall testing and its testing specifically in the area of mission scenarios.

Pathfinder also differed from previous missions in that the software and workstation environment used to do nearly all of its testing was the same as that used for mission operations. This allowed for automatic compatibility testing of ground and flight software as well as a phased approach to the development of Pathfinder's end-to-end-information system (EEIS). This EEIS included all ground software, flight software, flight hardware, and ground platforms necessary to complete the simulation of the "uplink through downlink" spacecraft environment.

SURFACE OPERATIONS FUNCTIONAL TESTING

From a surface operations verification perspective, the initial validation of the capabilities necessary for surface operations was completed in the Mars Pathfinder Flight System Testbed (FST). This test environment includes a flight like lander with rover, IMP, and ASIMET science instruments.

Initial flight software functionality tests were completed in the FST within a series of phased flight software deliveries. Once the basic functionality was verified, specific mission scenarios were validated by separate tests. These tests were performed to validate the scenarios such as high-gain antenna pointing at earth while on the surface of Mars and the ability of the IMP to identify the sun. Individual surface sequences were tested, modified, and retested as the mission scenario testing progressed.

In addition to the FST testing, several system level tests were identified and run on the spacecraft. The system level test program included validating the complete sol 1 and sol 2 mission on the spacecraft four times before launch. The tests included a solar thermal vacuum test involving running the lander through thermal cycles similar to those predicted for the surface of Mars.

SURFACE OPERATIONS OPERATIONAL READINESS TESTING

One of the areas where Pathfinder excelled in testing was in it's Operational Readiness Test (ORT) program. The project made every effort to perform as many tests in a flight-like configuration as possible. These tests were done in the Pathfinder sandbox. This sandbox portion of the FST offered an environment for performing realistic surface operations tests for the purpose of testing the operator's ability to make real-tinle decisions and assess the data.

The sandbox consists of a full scale model of the Pathfinder lander located in a room 10 In by 20 In in size. Fully functional airbags, retraction motors, petal actuators, accelerometers, high gain antenna, and IMP were mated to this lander. The room also contained sand and rocks for simulating a variety of Martian environments, especially useful to test the rover operators and drivers. This allowed for extensive and realistic testing of the landed and surface portions of the Pathfinder mission in a series of tests termed Operational Readiness Tests (ORTs).

Following is a list of the ORTS performed on Pathfinder: (Note that ORTS 1 & 2 were completed pre-launch and ORTS 3 - 7 were completed post-launch)

- •OR']'1 - Launch and Cruise
- •ORT2 - Launch, Cruise, EDL, and Sol 1 & 2
- •ORT3 - Sol 1 & 2 Nominal
- •0RT4 - Sol 1 & 2 LGA
- •0RT5 - Sol 1 - 6 Nominal
- •ORT 6 - Low power, no battery
- •OR]' 6a - Sol 1 Petal move
- •ORT 7 - Sols 1 -6 Nominal
- •ORT 7a -Sol 1 - LGA

The ORTS benefited the surface operations process in more ways than initially anticipated. Firstly, they were useful for identifying any flight software problems that were not found in system level testing. Although system level testing was rigorous, several days of full surface scenarios were not at tempted until the ORTS so flight software problems were encountered and fixed during these ORTS.

Secondly, the ORTS were valuable in determining the most valuable set of sequences, contingency plans, and surface command modules that were necessary in preparation for the surface mission. Also, the contents of the above items were validated in terms of function, timing, and feasibility of completion in the overall planned scenarios.

Most importantly, the ORTs prepared the team for chaos and confusion. During these ORTS the team developed the ability to determine what data were critical for choosing the next step in the process of accomplishing the sol 1 and sol 2 engineering object ives. ORTS prepared the team for the real-time decision making that was necessary in order to accomplish the primary engineering objectives of the first two days on Mars.

RESULTS - THE FIRST TWO DAYS

Although the Pathfinder events from landing through the first two days on Mars went well, several problems were encountered that caused the team to operate in a responsive mode and take two days instead of one to deploy the Sojourner rover. The primary problems faced were:

- •Rover petal airbag didn't retract completely
- •Longer than predicted lock-Lip times at DSN caused critical imaging data loss
- •Rover communications with lander appeared to be poor
- • The computer reset during the night on Sol 1

Figure 4 shows the actual activities as they occurred on sol 1 and sol 2. The first decision that caused us to move off of our nominal path was the decisions to lift the rover petal and retract the airbag. When viewing assessment images taken by the IMP, it was seen that the airbag near the rear ramp (the preferred rover egress ramp) was in a position that could be potentially hazardous to the rover as it egressed down the ramp. A sequence was modified and tested in real-time to lift the rover petal 45 degrees, retract the airbag for a maximum

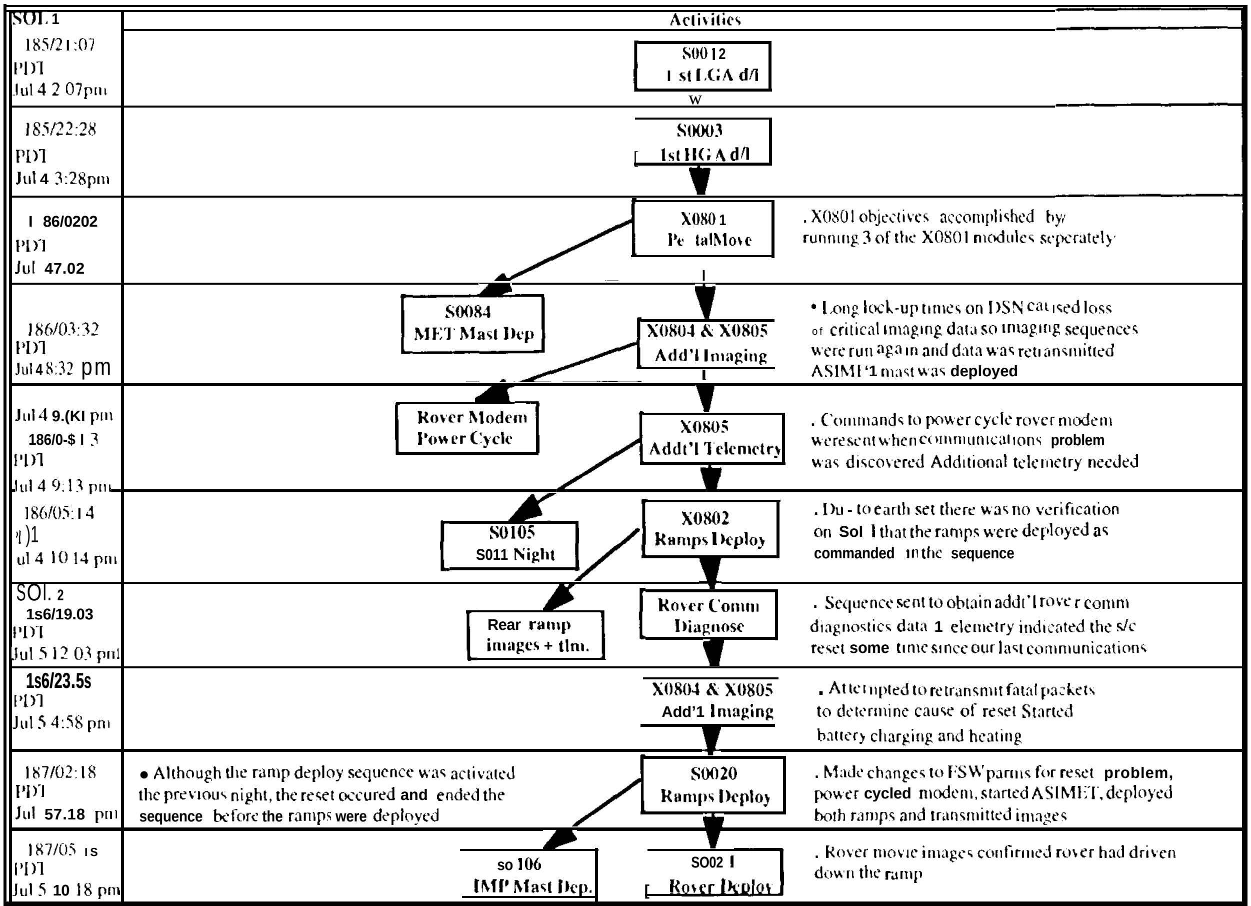

Figure 4: Sol 1 and Sol 2 Activity flow - Actual

of 600 seconds, re-open the rover petal to 110 degrees (its fully open position) and then update the lander's tilt information. This petal move sequence worked correctly but loss of the beginning of the rear ramp images due to longer than expected DSN lock-up times resulted in a necessary second attempt to take and downlink the same images.

At this point the telemetry indicated that there were possible rover communications problems with the lander. in addition to the attempt to retake and transmit rear ramp images, commands were sent to power cycle the rover modem and try to re-establish good communications between the rover and lander.

When the images were received and assessed, it was determined that both rover ramps (front and rear) should be deployed although the egress route for Sojourner would be via the rear ramp. A final set of commands sent while the earth was setting on Mars sol 1 stood up the rover, deployed both ramps and activated a nighttime sequence. Due to earth set on Mars, no verification of ramp deployment and rover stand-up was available that evening.

An attempt was made the morning of Sol 2 to downlink data that would help determine the cause of the rover communications problem. However, as we received our first data from the spacecraft, telemetry indicated that a system reset had occurred during the night. Fortunately, telemetry also indicated that the rover did receive it's morning sequence from the lander implying there was a better communication link between the two than on the previous day.

Additional images were taken after this first transmit session on sol 2 and commands were sent to determine the cause of the reset. Battery charging and heating were also started by command. Since the images indicated that the airbag was no longer a hazard to the rover, a decision was made to continue with the nominal ramp deployment and rover egress set of activities.

Although the ramp deploy sequence was activated the night of sol 1, the reset occurred such that the activities did not occur. Therefore, commands were sent to deploy both ramps, stand the rover up, and drive the rover off of the rear ramp.

The successful completion of the activities leading up to and including driving the rover off the ramp concluded a large portion of the Pathfinder engineering mission. Now, the lander is primarily a science station on Mars with all activities being focused towards acquiring imaging, weather, rover, and APXS data.

CONCLUSIONS

The success of the Mars Pathfinder project and specifically the extended mission on the surface speaks loudly about the approach taken to accomplish this task. There are also lessons learned from the surface operations test and verification program and they are described briefly below.

including mission scenario development and test in the early phases of spacecraft system testing was essential to understanding how to sequence and operate a spacecraft, particularly one with a need for team responsiveness to adverse surface conditions. Since the mission was planned for 30 days, all operational scenario testing dealt with expected conditions within those 30 days. As the mission extends longer, hindsight tells us that additional tests would have been useful in determining spacecraft operational issues later in the mission. (i.e. operation without the battery)

Using the same people and software to design, develop, test, and operate a mission enables a "faster, better, cheaper" approach to spacecraft development and operations. The experience and training necessary for operations is essentially "built-in" as a team members progress through the different phases of the project.

The sequencing architecture originally planned for surface operations 'was not modular but as testing progressed the architecture became highly modular. This allowed for semi-generic activities to be available for use without the need to anticipate every possible adverse surface condition and develop a plan for it.

Most importantly, planning and practicing for nominal and off-nominal scenarios in an operations-like environment is essential to the success of a mission such as Pathfinder. It was necessary that the team react quickly and correctly to the surface environment on the first two days on the surface in order to ensure the mission was a success. Without the grueling experiences of the ORTs, neither the spacecraft nor the team would have been properly prepared to accomplish the tasks of surface operations on Mars.

ACKNOWLEDGMENTS

All work described in this paper was performed by the Jet Propulsion Laboratory in pasadena CA. JPL is operated by the California Institute of Technology under contract with NASA.

REFERENCES

Gruel, David "Testbed Verification of Pathfinder's Martian Entry, Descent, and Landing (EDL)" 16th DASC Proceedings, October 1997.