

ASSEMBLY, TEST, AND LAUNCH OPERATIONS FOR THE MARS EXPLORATION ROVERS

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ABSTRACT

In January of 2004, NASA's twin Mars rovers, Spirit and Opportunity, successfully landed on opposite sides of the Red Planet after a seven month Earth to Mars cruise period. Both vehicles have operated well beyond their 90 day primary mission design life requirements. The Assembly, Test, and Launch Operations (ATLO) program for these missions presented unique technical and schedule challenges to the team at the Jet Propulsion Laboratory (JPL). Among these challenges were a highly compressed schedule and late deliveries leading to extended double shift staffing, dual spacecraft operations requiring test program diversification and resource arbitration, multiple atypical test configurations for airbag/rocket landings and surface mobility testing, and verification of an exceptionally large number of separations, deployments, and mechanisms. This paper discusses the flight system test philosophies and approach, and presents lessons learned.

KEYWORDS

Mars, assembly, testing, rovers, ATLO, Spirit, Opportunity

INTRODUCTION / PROJECT CHALLENGES

The Mars Exploration Rover (MER) Project was formed at NASA's Jet Propulsion Laboratory (JPL) in early 2000 in an effort to take advantage of the biannual Mars launch opportunity in mid-2003. The objective of the mission was to land a medium sized Rover on the surface of the planet for a 90 day primary mission. The spacecraft design consisted of a cruise stage on top of an entry aeroshell, a lander with airbags, and the Rover with its science instrument payload. Partially through 2000, the program expanded from one, to two identical vehicles.

SCHEDULE

From the beginning, schedule presented the greatest challenge to the MER team. The compressed development (3 years) was justified based on an assumed high degree of design leverage from the 1997 Mars Pathfinder mission, and minimal development time for the mature Athena science payload previously scheduled for flight on the cancelled 2001 Mars Lander. However, by 2001, mass growth and limitations in the inherited designs resulted in extensive spacecraft redesign and new development. These factors led in-turn to delayed detailed design work and hardware manufacturing, changes in contractor requirements, and ultimately a significant slip in hardware and software availability for system level integration and testing. The decision to build a second spacecraft also required another set of science instruments, which lagged the first deliveries.

Assembly, Test, and Launch Operations (ATLO) were scheduled to begin in February of 2002 for the first vehicle (designated MER #1) and April 2002 on the second vehicle (MER #2) to support the launch windows in May/June and June/July of 2003. The project levied an internal requirement to have both vehicles ready for the first launch window to minimize risk on the constrained planetary launch opportunity. In comparison to other JPL missions, the baseline schedule was aggressive for a vehicle of this complexity (Figure 1, 2). This problem was compounded by delays in the actual ATLO start dates to March and July of 2003, and further compounded by a number of late deliveries of critical hardware. In particular, the core flight avionics deliveries were not made until August and October of 2002 for MER #1 and MER #2 respectively.

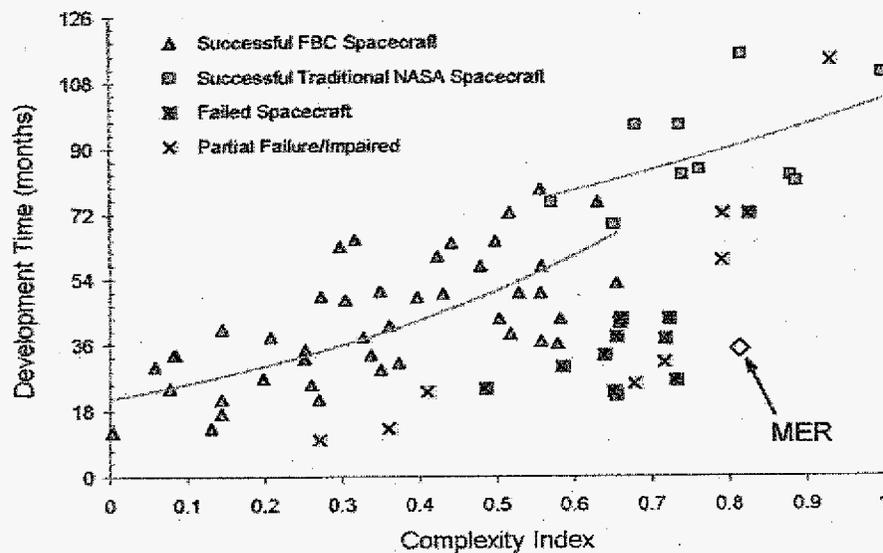


Figure 1 Spacecraft Schedule vs Complexity (ref 1)

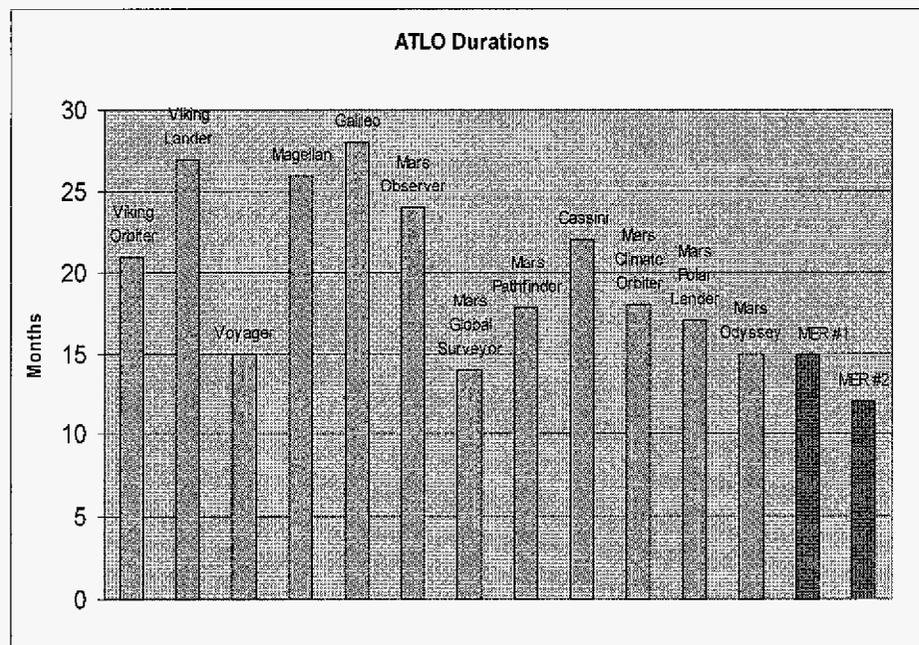


Figure 2 JPL ATLO Durations

Even after flight hardware deliveries were completed, the ramifications of the stressed development schedule continued to take its toll on the ATLO schedule. Late analysis work, and continuing testing by the subsystems, in the testbeds, and in ATLO drove out design flaws as system level activities progressed. These flaws ultimately demanded significant rework periods and associated regression testing of the flight hardware in January-March of 2003 prior to and after shipment of the vehicles to Kennedy Space Center (KSC). In addition, some assembly and validation activities that would otherwise have been performed at the subsystem level were deferred to the system level for the purpose of mitigating the ATLO delivery slips, but adding further scope to the system I&T activities.

SPACECRAFT COMPLEXITY

The MER vehicle complexity presented additional challenges for system level verification and validation. Figures 3 provide views of the system. The spacecraft was essentially a hyper-integrated combination of three missions: launch/cruise, entry/descent/landing, and Mars surface/science missions.

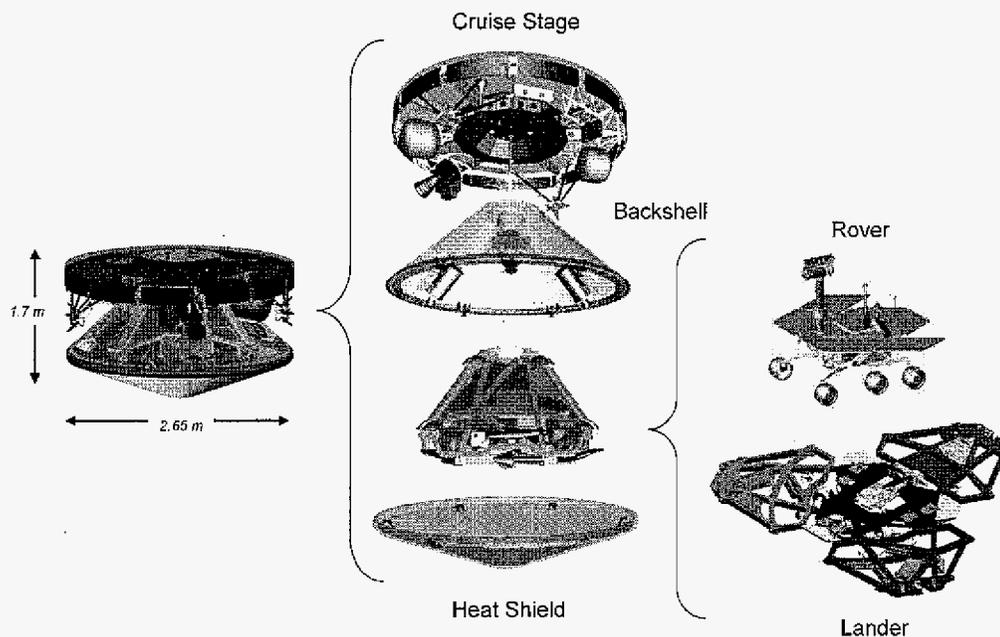


Figure 3 MER Spacecraft Configuration

The 165 kg Rover carried several camera's and science instruments distributed between the mast on the deck and the 5-DOF arm. The Rover also carried the only onboard computer, batteries, solar arrays, and power control electronics, x-band and UHF radios and antennas, thermal and mobility systems. During cruise and entry, the Rover chassis was broken and compressed, and the solar arrays folded to allow the vehicle to fit within the tetrahedral shaped lander. The lander provided a righting mechanism for the package after arrival on the surface, well as the protective airbags for the landing event itself. The lander was mounted inside the entry vehicle aeroshell, which also carried the landing retro and stability rockets, supersonic entry parachute, and an

inertial reference unit. Finally, the cruise stage provided solar power, propulsion and GNC sensors for the cruise phase of the mission. Pumps on the cruise stage circulated Freon in a cooling loop during cruise to move the heat generated deep in the spacecraft Rover systems out to cooling radiators on the cruise stage.

Figure 4 provides an overview of the entry, descent, and landing event timeline. During this period in the mission, the vehicle approaches the surface of the planet on a ballistic trajectory while systematically disassembling itself – starting with cruise stage separation and ending with Rover egress off of the Lander.

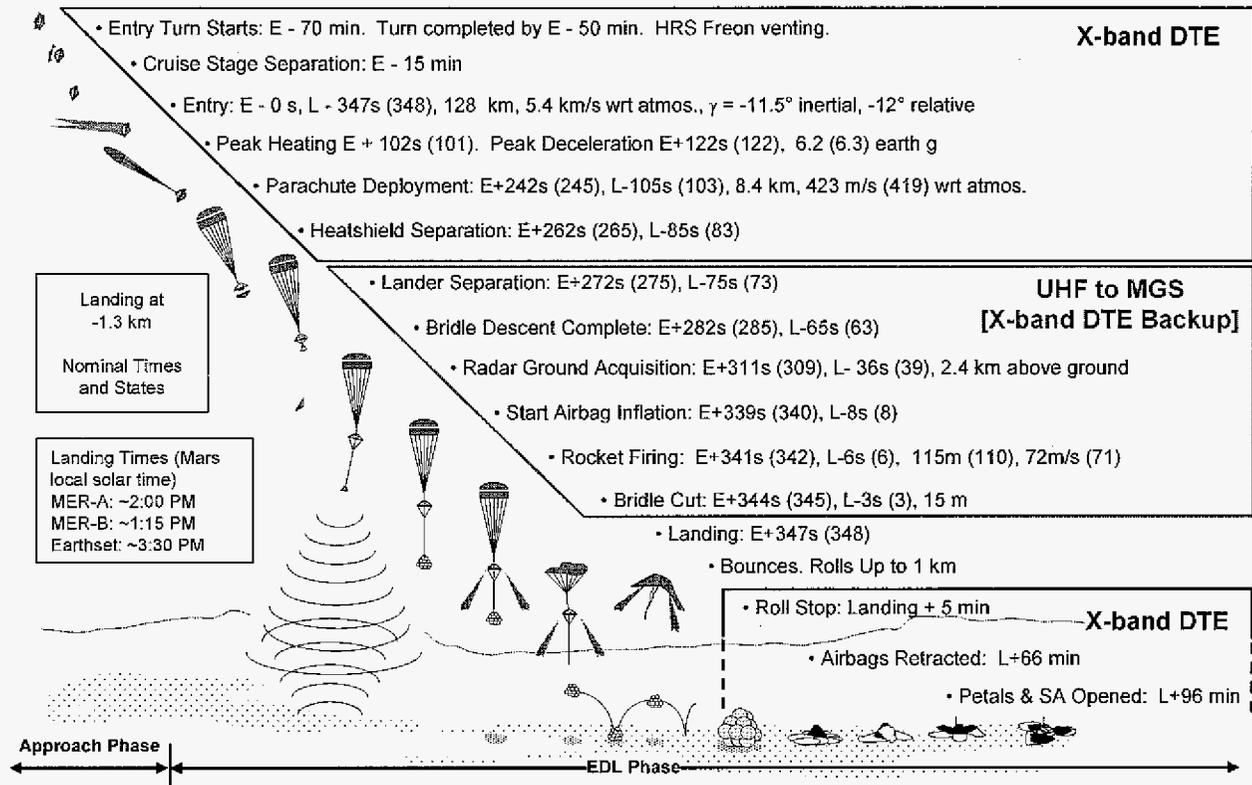


Figure 4 Entry, Descent, and Landing Timeline

The vehicle configuration and mission profile presented a number of unique system level integration and test issues:

Integrated Architecture: The integrated architecture made parallel I&T options on a given vehicle difficult or impossible. Unlike Viking for instance, which had orbiter and lander systems that were testable in a separable state, MER had a centralized command and data handling system on the Rover that was required for all phases of the mission from launch through surface operations. This demanded a level of serialization in the test flow that extended the critical path.

Mechanical Complexity: The system mechanical configuration of the spacecraft is often described using a 'Russian doll' analogy, where smaller systems are enveloped inside increasingly larger systems. Unfortunately, the implication at the system-level is that the long

and complicated system-level mechanical assembly cannot start until all elements of the 'smallest doll', the Rover, were available. ATLO was therefore unable to start the nearly two month process of stacking the spacecraft, until the C&DH that resided on the Rover was integrated.

Multi-phase Mission: Due to the multiple mission phases, and the various sub-phases in the entry, descent and landing period of the mission, the ATLO team was required to achieve an exceptionally large number of system test configurations. These ranged from a stand-alone rover capable of imaging/driving/arm manipulation/etc... on the floor of the highbay, to a full launch/cruise configuration. Other configurations included the Entry Vehicle only, the Backshell tied to Lander/Rover via a bridle, a stowed Rover on a Lander, a deployed Rover on a Lander, and so on. Figure 5 & 6 shows testing in the surface mobile and EDL EMI testing configurations respectively. All told, there were on the order of 10 different major system test configurations for each of the vehicles.

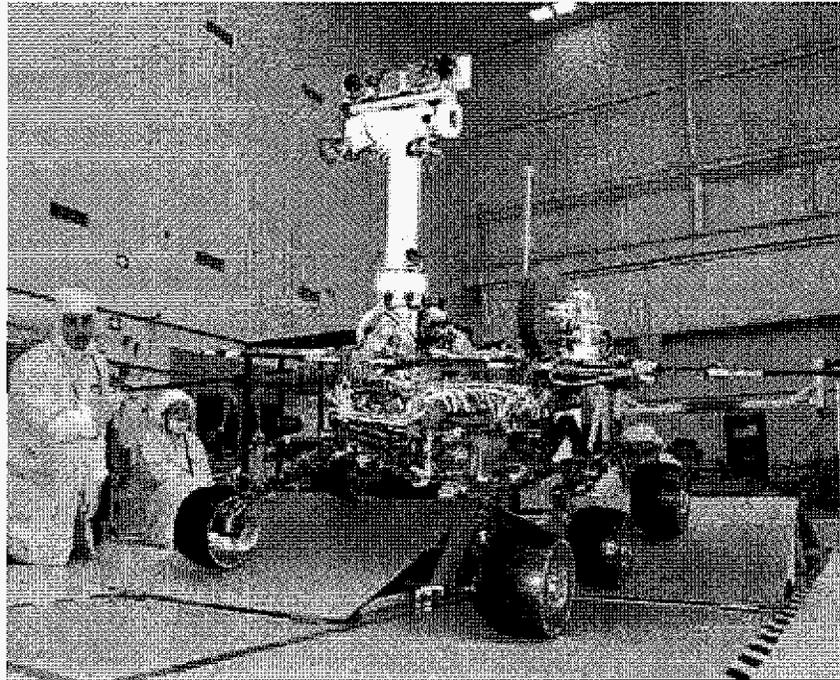


Figure 5 Rover Mobility Testing

Mechanisms/Deployments/Separations: Due to the nature of the mission and system architecture, each MER spacecraft carried over 40 mechanisms all of which were exercised in ATLO, and had 14 separation and deployment events of which 12 were testable on the flight spacecraft. There were more than 130 pyro circuits on the vehicle – all of the pyro circuit paths were validated and a high percentage had multiple live firings in test. Motor testing, phasing, range of motion, pyro-release, deployments, walkouts and clearance verification activities were performed multiple times per vehicle in most cases, placing a premium on both the technical experience of the personnel on the floor, the safety and quality assurance support, and the test planning process.

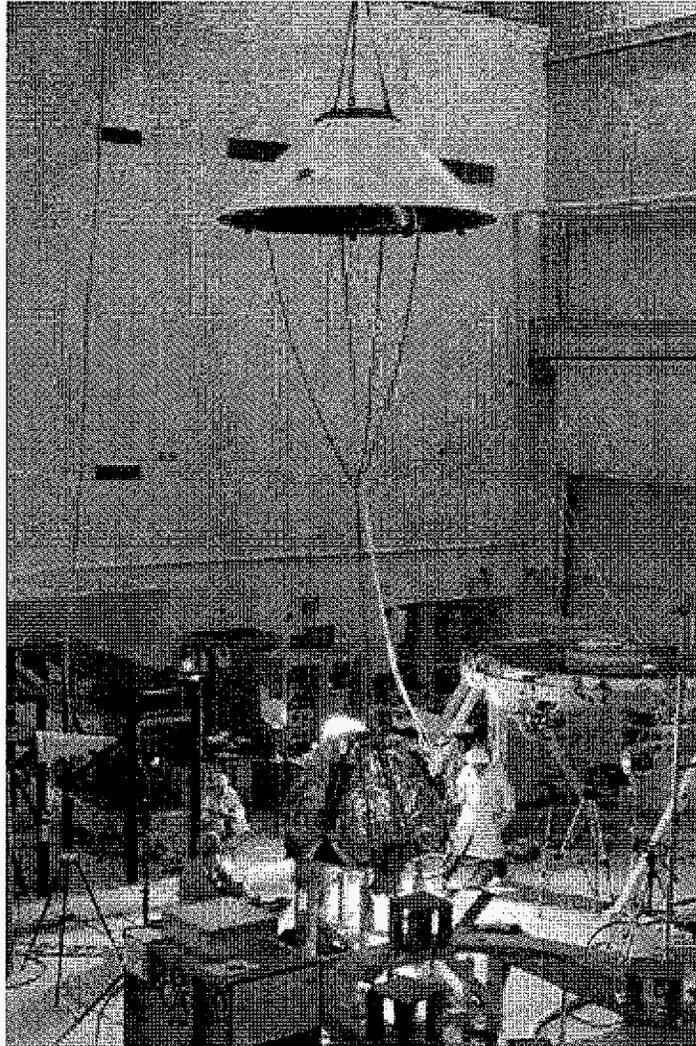


Figure 6 Entry, Descent, and Landing EMI Testing

Hardware Density: Hardware density on the vehicle was exceptionally high as a result of the volumetric constraints imposed by the inherited Mars Pathfinder EDL system. Continuous attention to critical clearances and mission unique assembly and handling support equipment to accommodate the visibility and assembly constraints were required in many instances. Figure 7 provides a view of the stowed Rover inside the Lander, with one Lander petal open.

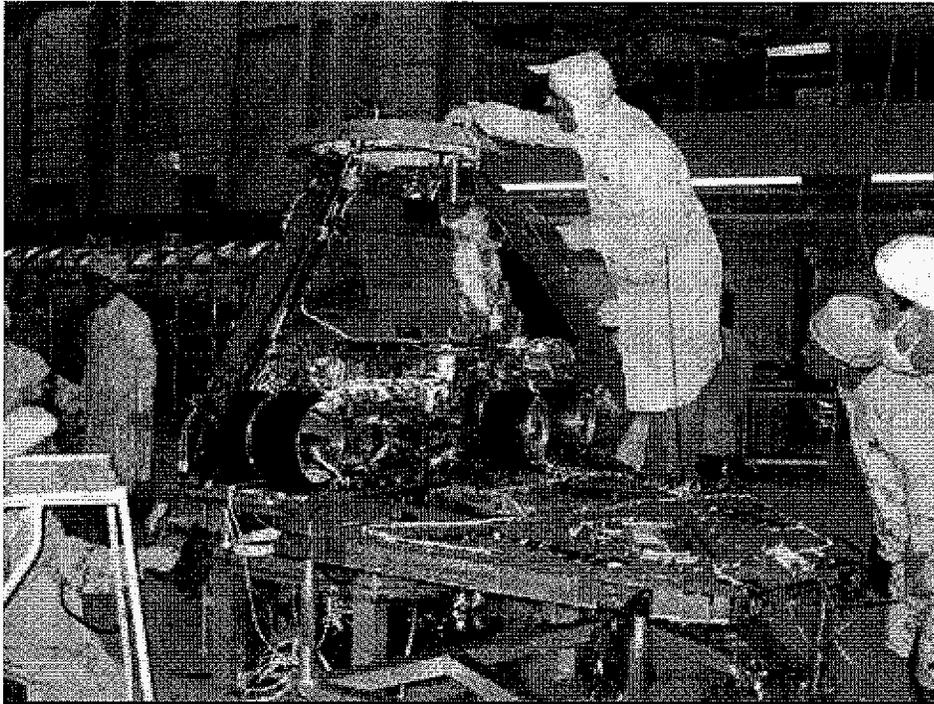


Figure 7 Rover Stowed in Lander

APPROACH/PHILOSOPHY

The project and ATLO management recognized many of the challenges that ATLO would face well before the heat of the battle began. These led to facility and in particular personnel selection and team structures that would maximize the responsiveness of the system.

STAFFING/SHIFTS

The project staffed many of the key ATLO positions as much as a year before ATLO start. This served the overall project well in that it allowed the management to develop into a cohesive team, to perform much of the long-lead planning to a greater depth than previous projects, and to interact heavily with the flight system and delivering organizations well before hardware was delivered. The result was that the ATLO leadership had good insight into the hardware status, likely schedule, maturity, weaknesses and liens. In addition, nearly all of the ATLO leads also supported the project in corollary functions prior to ATLO start, for example the electrical lead did some of the key integration work for the testbed, the ATLO coordinator was a delivery lead for the rover mast, etc... This approach resulted in minimal overall cost to the project as a result.

The project attacked the schedule problems on several fronts, including making plans for two shift ATLO operations. Although two shift and three shift operations had been used at JPL during ATLO campaigns in the past, this project was the first attempt to maintain two shifts over an extended duration. As a result, the project made an effort to discuss this issue with industry, notably with the Northrop Grumman Space Technology group in Redondo Beach, CA.

The team found that the two shift operations were particularly useful when properly timed. The first shift worked best when it started around 7:30am. Earlier starts were limited due to personnel carpooling and child care constraints. The second shift generally arrived between 1-2pm. The large amount of overlap between the shifts resulted in almost no loss of efficiency since there was typically a degree of off-line work required by the teams anyway. The early second shift start time also allowed test personnel to get home before 10pm generally.

Teams were staffed to allow critical path operations on either shift. Confining these activities to day shifts only created timing and efficiency losses. Mechanical and electrical test teams used a combination of face-to-face meetings, voicemail, email, and web-based test report tools to transfer critical information from one shift to the next. Outside of thermal vacuum testing, third shifts were only used with skeleton crews to generate hours on the hardware.

SYSTEM-LEVEL VERIFICATION AND VALIDATION

The MER project system-level verification and validation (V&V) was distributed across various venues. The flight program activities in ATLO were tied closely to these activities, particularly the structural verification program and the system testbeds. Personnel and procedures were shared among these teams to seed the early ATLO process. Complex functional and mission simulation tests were pre-run in these testbeds. Lengthy verification activities with characterization elements were generally pushed off the flight system critical path, and into these less time-critical arenas. And a significant effort was made to certify the fidelity of these venues against the flight system to allow verification activities to be performed in places other than the flight vehicles.

SCHEDULE & TEST FLOWS

The project adopted a number of working philosophies to accommodate schedule and test flow challenges throughout ATLO. Of these, one of the most important was simply to start. Three months after MER #1 ATLO start, less than 20% of the flight hardware had been delivered to the floor. The team however, had been moving forward with mockups, breadboards, engineering models, and partially tested flight hardware. This approach allowed them to validate procedures and expected values, create familiarity with the hardware, and exercise team and teaming arrangements – especially the critical two shift operations.

The ATLO flow and test philosophy was heavily influenced by having two identical flight vehicles in the program. JPL had not attempted a dual spacecraft mission since the Viking and Voyager programs more than 25 years earlier. An attempt was made to resurrect the test program philosophies for these missions via documentation review and discussions with personnel involved. As the MER test program evolved, it became clear that while simultaneous operations on two large spacecraft would stress certain management and facility resources, the second test platform would present opportunities that ultimately could enable the compressed schedule to be met. The authors believe that had MER not been a dual spacecraft mission, the project in all likelihood would not have achieved the aggregate system-level testing required to successfully launch and land the vehicles.

The MER #1 and MER #2 ATLO starts were offset due to hardware availability out of the manufacturing pipeline. Early in the test planning, it became clear that completing an identical

traditional test program on both vehicles would threaten the schedule viability of the delayed second vehicle, and potentially the first as well. As a result, the team began to develop ideas for leveraging the second vehicle in a manner that would not impeach the overall integrity of the test program for either. Several key policies and test philosophies were identified, reviewed, and adopted into the test program:

Test Diversification: MER ATLO took advantage of the identical nature of the two spacecraft to diversify testing in the two flows. Specifically, there were design, model validation, FSW, operability, and end-to-end tests that were performed on one vehicle, that were not always repeated on the following vehicle. Launch configuration EMI radiated emissions and susceptibility testing, for example, was only performed on MER #1. The most significant example of this was an option exercised on the second vehicle that descope the full launch/cruise dynamic and thermal testing. The descope was mitigated with a partial test of the critical hardware for these environments (Cruise Stage & Aeroshell only), which still allowed the critical path through the Rover testing to continue in parallel. This ultimately led to a slingshot effect for MER #2 which accelerated it into the first launch window ahead of MER #1.

Problem Retest: The following vehicle was frequently used for retesting problems found on the lead vehicle. This often allowed the lead vehicle test program to move forward into new configurations (for example out of the thermal vacuum chamber), with the knowledge that the other vehicle would eventually present a retest opportunity.

Hardware Sharing: The project explicitly excluded requirements for cross-platform compatibility testing (ie, that either Rover could be mated to either Lander), however the design restrictions on the hardware required compatibility in nearly all cases – though some tailoring (shimming for instance) was unavoidable. MER took full advantage of this feature by moving hardware at the box or assembly level where required from one test flow to the other to support functional testing and maintain schedule. A similar approach was taken with the electrical ground support equipment, minimizing the number of times the test complexes were broken down and moved as the spacecraft cycled through different test facilities.

Early Risk Retirement: The project was able to initially focus on different functionality for the two spacecraft, thereby retiring various risks earlier in the program. Specifically, MER #1 initial ATLO objectives were to complete launch/cruise configuration assembly and testing, with Rover/surface science testing delayed until late in the flow. MER #2 ATLO flow was reversed, allowing design risks for both mission phases to be addressed earlier in development.

Surge Capability: Both vehicles were shipped to the launch site in time to support the first launch opportunity. At that point, the project decided to slow work on MER #1, thereby allowing a greater focus on preparation of MER #2 for the first launch, specifically the critical final mechanical assembly work. This type of surging, ie biasing the dual spacecraft staffing toward one vehicle or the other, was done frequently throughout ATLO on a shift-by-shift or day-by-day basis when there was an uneven work load requirement.

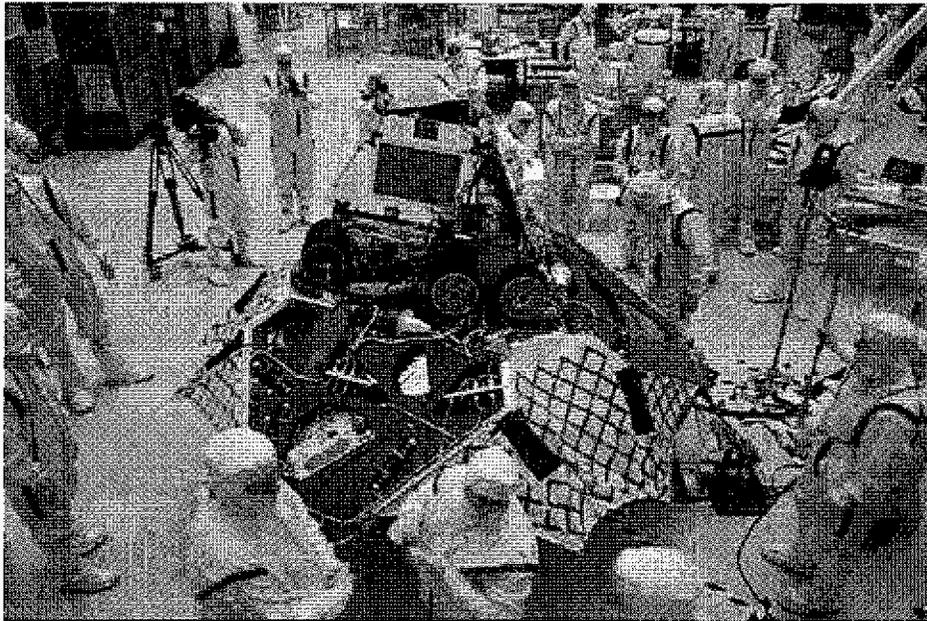


Figure 1 Lander Deployment Testing

RESULTS

Both vehicles successfully launched in the early summer of 2003. There have been three anomalies in-flight of note. One of these, a heater switch that was found to be stuck in the 'on' position, is still unexplained. The other two, a flash memory management software problem on Spirit shortly after landing, and an unexpected voltage delay problem prior to entry on both vehicles, have root causes that are now well understood. From a lessons learned perspective, both of these might have been identified during system level testing had a more systematic data review process been executed. This is likely the most significant fallout of the accelerated ATLO schedule.

Despite these issues, the missions have on the whole been very successful. General vehicle performance throughout the cruise period was good. Entry, descent, and landing were successfully executed, and surface operations have been successful though some non-critical life-time issues have arisen. As of the time of this writing, both Spirit and Opportunity were still successfully roving the Red Planet, having outlived their 90 day primary mission duration, and combined to accumulated more than 600 sols (Mars days) on the surface.

It's worthwhile to note that innovative planning and approaches can only achieve so much. Ultimately, it was the MER ATLO and flight system development team that created the gap between success and failure. The statistics listed below provide a measure of the extraordinary effort these men and women contributed to this mission.

- 51 out of 52 weekends with ATLO work between 2002 and June 2003
- 3170 hardware items tracked in ATLO
- 1200 (approx) inspection reports
- 15,000 (approximate) flight and GSE connector mates in ATLO
- 36,000 (approx) pages of released ATLO procedures
- 8 rover assemblies (6 disassemblies) over 9 months
- 27 system level environmental tests between over 7 months: 5 thermal tests, 4 EMI tests, 4 dynamic tests, 5 pyro system tests, 9 spin balances.

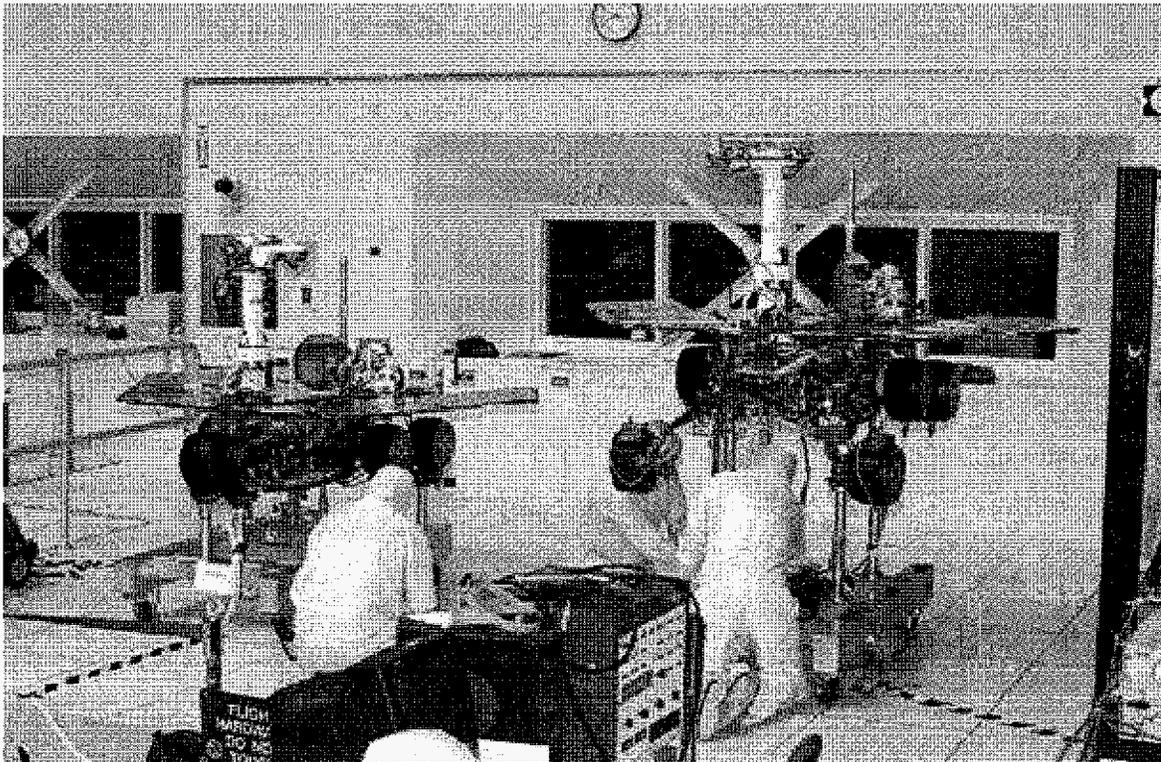


Figure 2 MER #1 (Opportunity) & MER #2 (Spirit) in ATLO

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1. Aviation Week and Space Technology. May 16, 2003