MER: From Landing to Six Wheels on Mars…Twice

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Abstract – *Application of the Pathfinder landing system design to enclose the much larger Mars Exploration Rover required a variety of Rover deployments to achieve the surface driving configuration. The project schedule demanded that software design, engineering model test, and flight hardware build to be accomplished in parallel. This challenge was met through (a) bounding unknown environments against which to design and test, (b) early mechanical prototype testing, (c) constraining the scope of on-board autonomy to survival-critical deployments, (d) executing a balance of nominal and off-nominal test cases, (e) developing off-nominal event mitigation techniques before landing, (f) flexible replanning in response to surprises during operations. Here is discussed several specific events encountered during initial MER surface operations.*

Keywords: MER, Rover Deployments, Airbags, Standup, Egress.

1 Introduction

The Mars Exploration Rover (MER) project was initiated in 2000, and successfully landed and operated two Rovers on the surface of Mars using a Pathfinder-like airbag system. The mission period from surface Impact to Egress (ITE) encompassed all the deployments achieved during the initial days. The design required a strict time-ordering of operational events described by a veteran of the Viking mission as, "…the most complicated and fascinating engineering sequence ever done on a robotic mission" [1] This phase culminated in the Rover drive off of the Lander ('six wheels on Mars') to begin Surface Science operations [2, 3]. Instrument health checks and science imaging were interleaved among the major ITE engineering activities of Critical Deployments, Standup, and Egress (See Figure 1). Here is provided specific design, test and operational experiences from this phase of MER.

The rapid project schedule of less than 4 years from inception to landing dictated a one-pass design process wherein a key challenge was fitting the Rover within the volume-constrained Pathfinder-based landing system. The resulting deployment design used 34 motors and 27 pyro devices. Engineering models (EMs) and flight hardware were built in parallel, such that issues discovered in test generally needed to be met with software and/or operational solutions. As in any surface mission, terrain interactions were only testable with EMs to preserve the integrity of flight hardware.

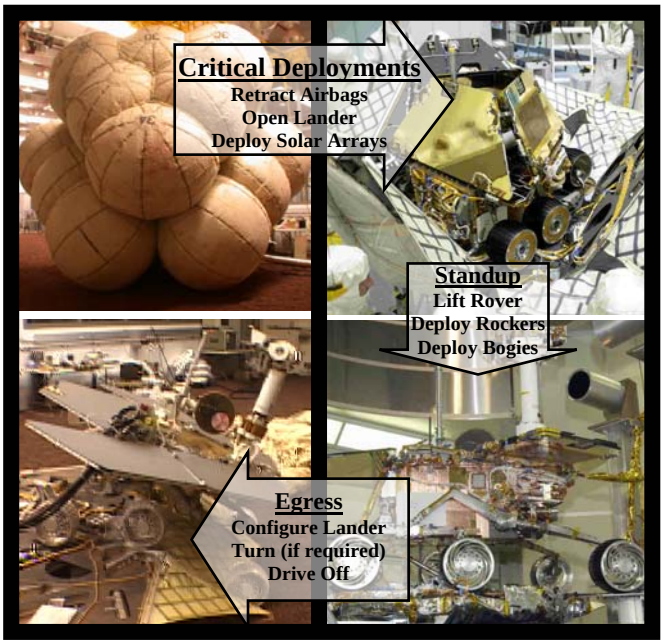

Figure 1. Surface Deployment Configuration Changes

Critical Deployments software autonomously righted the Lander onto the Base petal and achieved a safe, power-positive state with Rover solar arrays deployed before nightfall. Electronics mounted to the Lander were not designed to survive the night. Pyro releases controlled by Lander electronics were therefore accomplished, including release of the Rover body, the front wheels, the camera mast and cutting the first of 3 cable bundles to the Lander. The Camera mast was deployed to return images via relay through the Odyssey spacecraft on landing day. The Rover avionics then shut down for the night to conserve battery power and awoke the next morning for the first direct-to-earth ground communications sessions. The Operations team directed a cut of the second cable bundle to the lander

and began the step-by-step Standup procedure to deploy the Rover rocker-bogie mobility system. In preparation for Egress, the instrument deployment device was released from its launch locks and stowed for driving. The lander petals and airbags were adjusted to optimize the driving path. The Operations team then commanded the cut of the final cable bundle and drove the Rover onto the Martian surface.

The design led to a number of interdependencies among these deployments. Tighter airbag retraction was a benefit to Lander petal deployment, but could ultimately result in a high Lander deck making Egress more difficult. Lander Tilt relative to gravity potentially poses a risk to Standup, but can be a benefit to Egress. Solar array deployment caused visual obscuration of two small patches of terrain, leading to uncertainty in potential Egress paths other than generally straight. A variety of contingency plans were tested with EM hardware in terrain prior to landing. These tests served to prepare the team to balance competing requirements during operations.

The Science team desired a large set of observations from the high vantage point the Lander afforded. Science sequences were defined, modularized, and tested before landing. This enabled the operations team to flexibly interweave science sequences between replanned engineering events. Up to four decision cycles were achieved per day with verification of success via imagery and telemetry. Standup operations took place in parallel with Egress EM testing before committing to the drive in flight.

Post-egress, the team had two weeks to implement parameter and sequence changes from Spirit ITE lessons learned. Then Opportunity landed to begin a second ITE with Critical Deployments.

2 Critical Deployments

Autonomous critical deployments begin when the Lander/Airbag comes to a rest, and ends when the rover has safely deployed its solar panels and reconfigured itself for self-sustaining operations on the Martian surface. This process takes approximately 80 to 120 minutes, and in some off-nominal cases may even carry on into the following Sol. Over the course of the critical deployments, 18 pyrotechnic devices are fired, and 16 motors are utilized to mechanically transform the spacecraft.

2.1 Critical Deploy Test Program

Development, validation and verification of the complex critical deploy phase was performed using the EM testbed, typically with simulators and scripts providing the inputs to the test environment. The test program was augmented with physical hardware -- an actuated Lander with petal and airbag actuators, an Inertial Measurement Unit (IMU) and EM airbags. Several hardware-in-the-loop tests were conducted after manual exploration had established the appropriate parameters for airbag retraction and petal deploy. The test program finished out with operational readiness tests running the flight algorithm, unattended, as would be the case in flight.

2.2 Spirit Critical Deploy

The Airbag system can come to rest while transmitting a carrier signal in any orientation. Earth was low on the horizon, and hence continuity in receipt of the transmitted signal was not guaranteed. The first act of critical deploy is to signal its state, including which petal is down, through a series of four semaphores (aka tones). Tones were transmitted first through the Rover Low Gain Antenna (RLGA) and then through an opposing antenna mounted on the bottom of the Lander basepetal. The strong X-Band signal transmitted by Spirit throughout EDL vanished about two minutes after landing. 16 minutes of silence was broken at precisely the expected time for the basepetal antenna tones. The operations team was both relieved and puzzled at receiving a 'base petal down' (right side up) tone coming out of the base petal antenna (indicative of upside down). An examination of the Earth geometry and the tilt history revealed that the Lander was held up by partially inflated airbags on the threshold between 'side-down' and 'base-down', with its base petal antenna pointed in the direction of Earth (64° off-boresight). Received signal strength provided additional confirmation of this orientation.

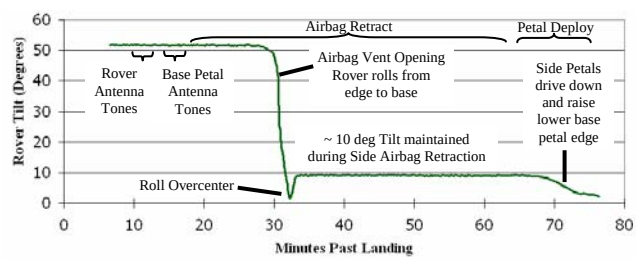

Figure 2. Spirit Critical Deploy Tilt History

Figure 2 illustrates Spirit's time-profile of tilt, and a substantial portion of the total knowledge the flight software had of its environment during deployment. Both Spirit and Opportunity experienced softer landings [4] than the stressing cases for which the airbags were designed [5], and as such, they remained fully inflated until vents were opened by the airbag retraction process. This can be seen from the transition from ~50° to approximately 10° about 30 minutes after landing. The nearly 40 minutes spent at an angle of 10° cannot be explained by airbag retraction, so it is either due to a rock or perhaps a hollow in the terrain under the Lander. A rock up to ~20cm in height could produce this tilt, and an inspection of the landing site reveals several rocks approaching this size. The tilt was

removed when the Lander side petals deployed to the iron-cross (flat) configuration ~70 minutes after landing.

Now free to deploy, the three primary solar arrays did so after 15 seconds of motion, and the two secondary arrays followed after 29 seconds of motion. Having successfully achieved a power-positive state with no anomalies, the Panoramic Camera Mast was deployed in 52 seconds to begin imaging (Figure 3). Deployment of the high gain antenna was commanded by the ground the following Sol.

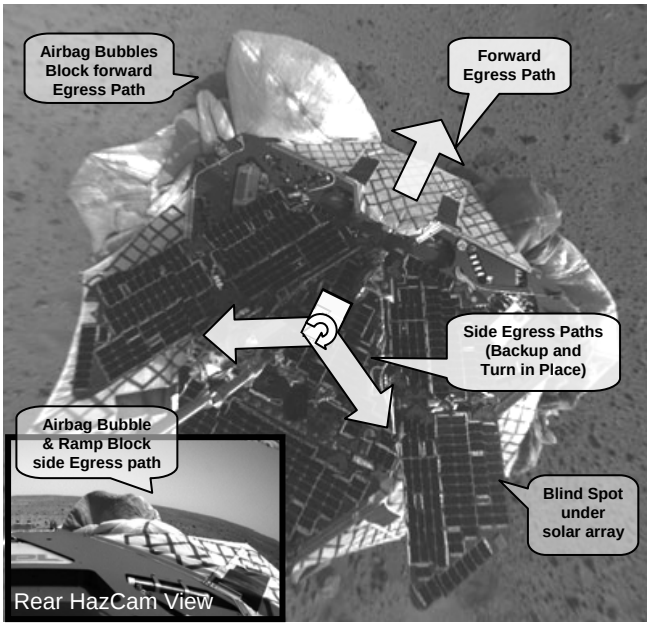

Figure 3 Spirit Airbag and Egress Ramp Configuration

2.3 Opportunity Critical Deploy

Opportunity maintained a continuous signal following landing, and reported its status tones through the RLGA. The tones indicated that the Lander was on the side petal in the rear direction of the rover. This would be the first execution in flight of the 'side-down' algorithm to right the Lander orientation, since both Pathfinder and Spirit landed base down.

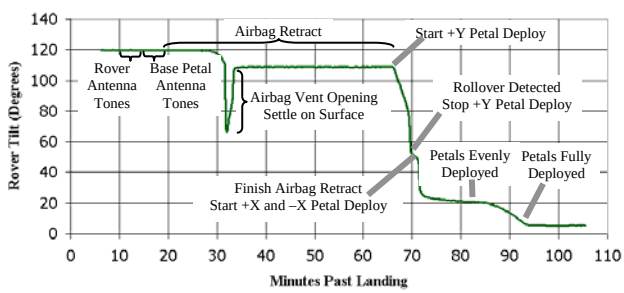

Figure 4. Opportunity Critical Deploy Tilt History

Figure 4 shows the tilt history for Opportunity's side-down case. Airbag retraction initiated with the airbags still fully inflated, and the Lander oriented at approximately 10° off a pure side-down orientation (110°). The airbag retraction process pulled open the vents at ~ 32 minutes, and the Lander is observed to list towards one edge before settling on the +Y petal. The Lander is likely resting on a combination of the tip of the +Y petal and the gas generator mounted on the backside of the petal used to inflate the airbags during EDL, providing for a few degrees difference from the nominal 110°. The airbag that the lander is resting on retracts partially (~80%) to prevent unnecessary stress on the airbag retraction cords. The first segment of airbag retraction is complete about 67 minutes after landing, and the lander initiates a deployment of the +Y petal to 70° to induce a roll onto its basepetal. The tilt history at 72 minutes indicates that, similar to behavior observed in test, the 'rollover event' isn't a sudden event but rather a 'mush over'. Petal deployment is then paused and +Y airbag retraction is completed. The other two petals are deployed to even out with the +Y petal and then all petals are deployed to 112° in about 9.5 minutes. The rest of critical deploy unfolded as nominally as Spirit. As Opportunity landed earlier in the Martian day, it had more time margin against the overflight of Mars Odyssey and the UHF Relay transmission, and had ample time to acquire images on its first day on the surface (Figure 5).

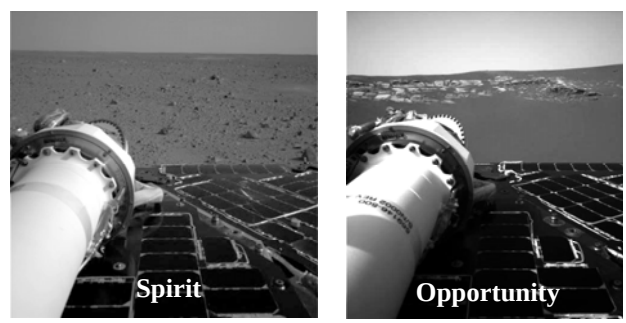

Figure 5: First views from pre-deployed PANCAM mast

3 Rover Standup

3.1 Standup Overview

The MER vehicle employs a novel, six-wheeled mobility system shown to aid its traverse across the Martian surface. Linking the wheels together is a rocker-bogie suspension system, shown in Figure 6, consisting of two primary structural elements (the rocker and bogie) connected together by means of free pivots at the rocker-bogie interface. Stowage of the MER vehicle and this mobility system within the available envelope of its tetrahedron-shaped lander was one of the most significant technical changes faced by the rover's design team. To facilitate this stowage, the rover suspension system was "broken" at 6 locations (3 symmetric pairs – port and starboard sides of the mobility system), allowing the vehicle the ability fold to fit within the compact lander envelope [6, 7]: a) at the rocker-bridge joints connecting the forward and aft rockers, b) between the rocker bridge and the forward rocker

structure, and c) between the aft bogie and forward bogie structural elements (see Figure 6). Transforming the rover from this stowed configuration required a complex, four-step process, sequentially deploying the vehicle and its mobility system to its final traverse state. Each element of the stand up process was completed autonomously on the vehicle and then verified by flight controllers on the ground before continuing with the next step in the sequence. This process of rover standup and deployment is outlined in Figure 7.

Standup Part 1, the first step in the process, centered around the lift of the rover's chassis off the lander base petal, deployment of the vehicle's two front rocker wheels, and latching of the rocker bridge joints. Rover lift was accomplished by means of a lander-mounted Rover Lift Mechanism (RLM). The RLM served as one element of a four-bar linkage arrangement along with the suspension's aft rocker elements, raising the chassis to the full extension of the RLM's lead screw actuator (first panel of Figure 7). Once in position, the front wheels were deployed. Stowed in an inverted position, the front wheels were swung 180 degrees and locked into their deployed state by means of two rotary Rocker Deployment Actuators (RDAs), located between the front rocker structure and the rocker bridge joint. Finally, the system was lowered on the RLM to an intermediate position of 183 mm of extension, with the front rocker wheels hovering just above the lander base petal. This act of raising and lowering the rover also results in locking out the rocker-bridge joint, securing a primary structural latch (see Figure 6 inset) that allows the vehicle to stand on its own.

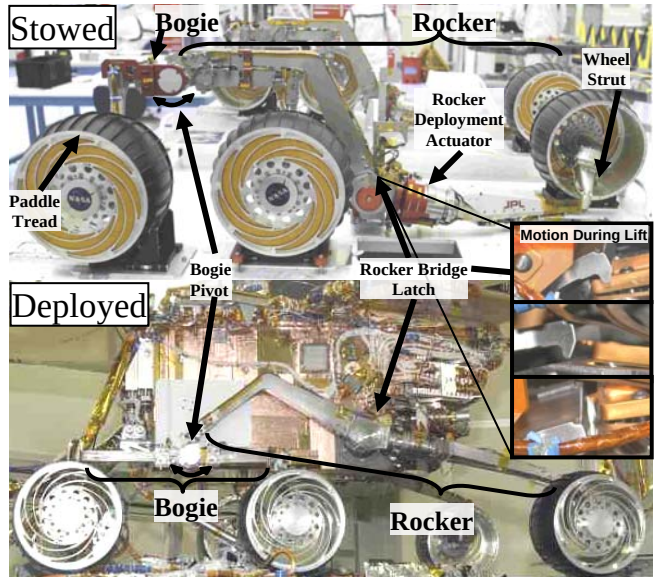

Figure 6 – Suspension System Nomenclature

Standup Part 2 consisted of re-raise of the rover immediately followed by a lowering motion back to the 183mm position on the RLM. This step was added during the surface operational readiness test (SORT) because confirmation of the latched state of the rocker bridge could not be reliably completed from data collected during Standup, Part 1. Instead, the vehicle pitch information from its IMU was used to verify that the rover's kinematic state had changed due to the latched rocker bridge. If either latch had failed to engage, the vehicle's pitch behavior during Standup Part 2 would have been significantly different. The data from the IMU therefore provided an unambiguous determination of the rocker bridge latch state, allowing the

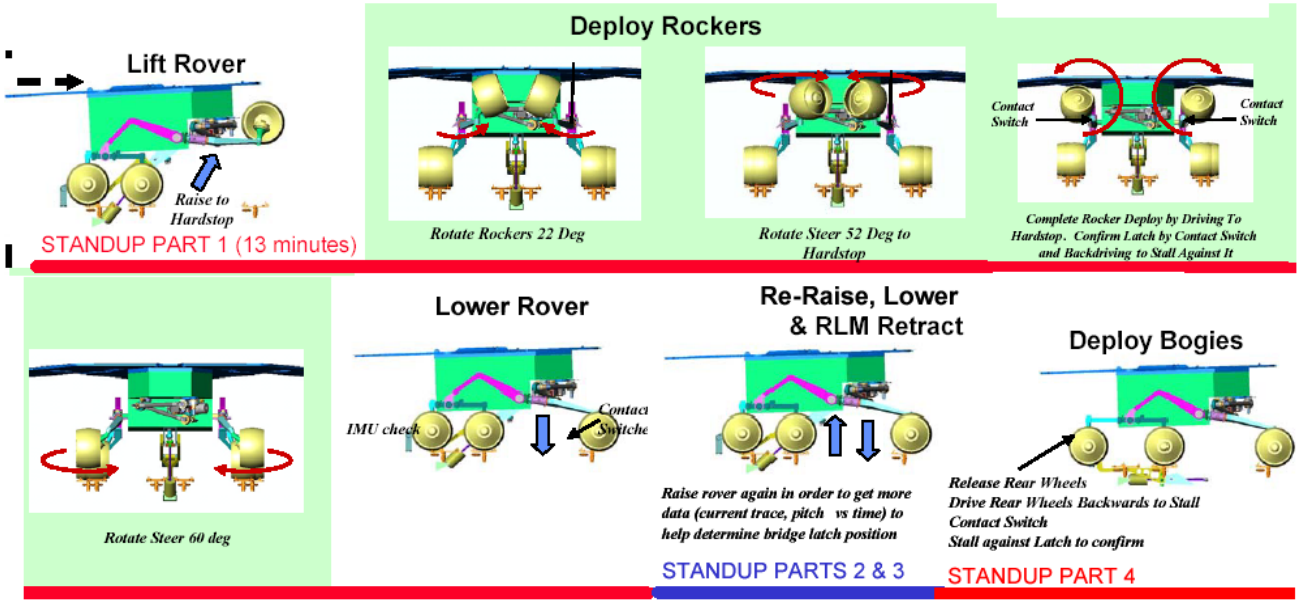

Figure 7 Rover Standup Process

rest of the standup sequence to continue with confidence.

Once the latch state was confirmed, Standup Part 3 was initiated, during which the RLM was retracted to its fully stowed position. Retracting the RLM had the effect of setting the front wheels down on the lander base petal, the weight of the rover now upon them.

Standup Part 4 consisted of bogie release and deployment. After pyrotechnic release of the rear wheels, deployment was accomplished by commanding the rear wheel to drive away from its launch restraint. The wheel gained traction for this motion by means of a cogged platform secured to the lander base petal.

3.2 Standup Test Program

The standup system Verification and Validation (V&V) program and the associated hardware characterization program was run on a total of four different test vehicles: the Rover Dynamic Test Model (DTM); the Mobility Test Model (MTM); the two flight vehicles; and the DTM and MTM rovers fitted with avionics as part of Surface Operational Readiness Tests (SORTS). Across these different test vehicles, nearly 100 individual tests of standup-related hardware were completed. Of these tests, three were completed at the expected worst case cold temperatures. One of the key outputs of the test program was the insight that some of the primary behaviors of the compliant 4-bar linkage determined the precise position where rocker bridge latching occurred. Results of this test program helped shape the in-flight verification of this latch state and the related design of the Standup Part 2 sequence.

Although the core mechanical and flight software architecture for achieving standup were found to be sound, the test program uncovered a total of seven different hardware modifications required to ensure standup success on Mars [6,7]. In addition, the test program, together with dynamic analysis using ADAMS simulation, provided a more complete understanding of the behavior of the system. A purely analytical approach to the problem was not possible due to the compliant nature of the suspension system and the multitude of joints and mechanical interfaces.

3.3 Spirit Standup Results

The first flight implementation of the rover standup sequence occurred on the MER Spirit vehicle. Standup Parts 1 and 2 occurred on Sol 6 of the surface mission, with the rest of the sequence concluding on Sol 7. During Standup Part 2, the vehicle completed a re-raise to 210 mm of RLM stroke. This motion, while used as a successful latch state indicator on the EM vehicles, resulted in an ambiguous pitch signature from the IMU. It was determined that an additional re-raise to 215 mm was needed to clarify the rocker bridge latch state. This additional motion, deemed Standup 2.5, was added to the plan and completed in the morning of Sol 7, resulting in a successful indication of rocker bridge latching. Following this added step, RLM retraction and bogie deployment, Parts 3 and 4, occurred as expected, with vehicle deployment complete by the end of Sol 7. Figure 8 shows the differences between the expected vehicle pitch behavior seen during EM vehicle testing and the actual flight performance on Spirit during Standup Part 2.5, with the flight behavior lagging the expected behavior from test.

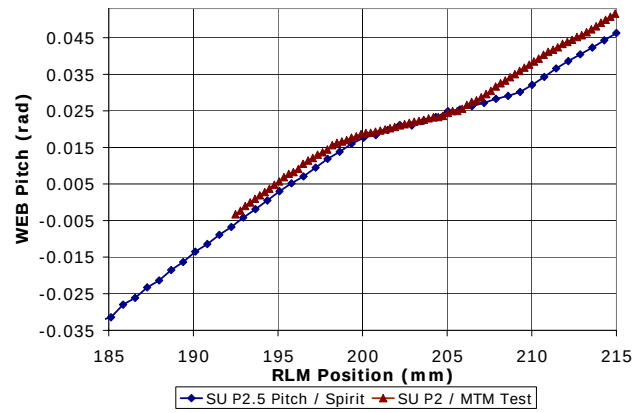

Figure 8 – Flight / Test Pitch Data from SU Part 2 / 2.5

3.4 Opportunity Standup Results

Based on the experience from Spirit, Standup Part 2 was altered to re-raise to 215 mm of RLM stroke, instead of the original 210 mm. With this change made, Opportunity standup began on Sol 4 with Standup Parts 1 and 2. These steps completed successfully, allowing the addition of pre-egress preparatory activities into the standup flow. The remaining vehicle deployments successfully completed on Sol 5, leaving the vehicle ready for Egress preparations.

4 Rover Egress

4.1 Egress Overview

The Rover is designed to drive down any of the three ramps (see Figure 3) within a heading +/-30 degrees of the ramp centerlines. The forward path is generally safest for two reasons: the deployed solar arrays create blind spots along the two side ramp paths, and the rover wheels encounter fewer obstacles on the Lander deck than during the backup and turn in place (TIP) required for a side path. Unlike natural terrain, the Lander hardware has edges and reentrant angles in places which could snag a wheel rim.

The wheel paddle tread design (see Figure 6) featured smooth surfaces to preclude snags on ramps or airbags, albeit at the cost of traction on the Lander and terrain. As a result, tests showed that the Rover experiences short skids (< 5cm) at tilts up to ~ 10 degrees, and longer skids at steeper tilts. This behavior was taken into account in deciding upon Egress paths in flight.

The rover retains control of the airbag retraction actuators and lander petal actuators until cutting the cable just before driving. Lander tilt and height can be improved by further retracting airbags or by changing the angles of the petals. The result of actuations is affected by location and size of rocks and airbag bunches beneath the Lander, integrity of retraction cords, etc., such that predictions of final Lander state are necessarily approximate.

Planning for Egress began on Landing day with the stereo images of the environment used to determine potential hazards, deck height relative to ground, and ramp deployment state. This analysis was used to evaluate the relative risk of different paths, and how that risk might be mitigated by airbag or Lander petal actuation.

4.2 Spirit Egress

The forward Egress path was partially blocked by an under-retracted airbag (Figure 9) and one of the side paths was blocked by an Egress ramp propped up by airbags (Figure 3 inset). Risks along the side path motivated an additional airbag retraction in an attempt to clear the forward path. Airbag motion was less than required, possibly due to a broken airbag retraction cord and/or material pinned between the lander underside and rocks.

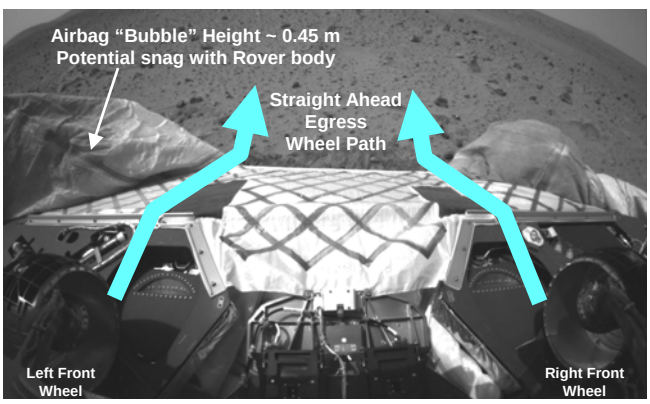

Figure 9 Airbags block Spirit Forward Egress Path

The side egress path was tested using an EM Rover and Lander to verify hazard clearances and gather imagery of predicted wheel locations at specific waypoints. The turn of ~120° was implemented in several discrete moves to enable operators to assess position and correct if necessary.

An error in positioning the rover by >1cm could result in a wheel getting snagged on a Rover-Lander restraint feature. This condition was created in test to demonstrate that, in the event of a snag, the mobility system had adequate torque to shear the restraint off of the Lander. Figure 10 shows rear hazcam views of the wheel and the restraint at the three turn steps to the final Egress position. The two right-most images in the series compare Spirit and testbed images were compared by operators to confirm clearance of the hazard.

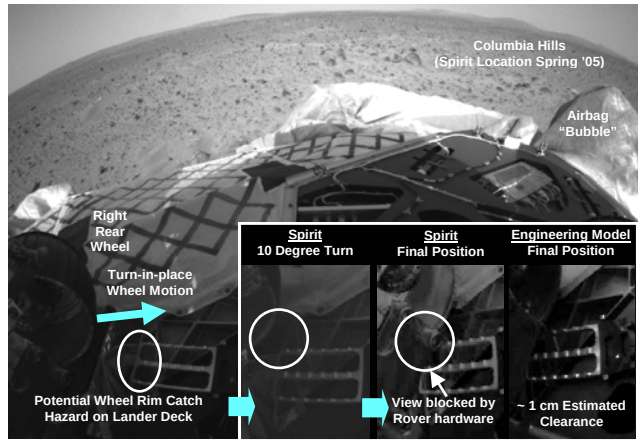

Figure 10 Test to verify Spirit Egress Hazard Clearance

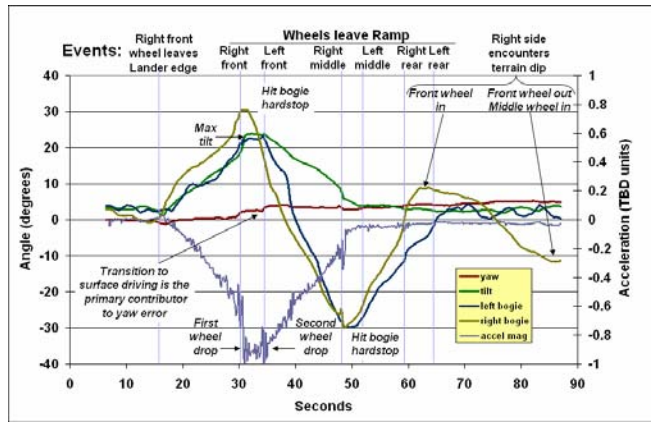

Figure 11 Spirit Egress events visible in telemetry

Egress consisted of a 3m straight drive off of the Lander (see Figure 11). The ~23 degree tilt down the ramps was a record not broken for many months. Wheel drops can be seen in the acceleration data causing shifts in yaw. Rotation about the bogie pivot (see figure 6) shows the forward rotation of the suspension system until the front wheels hit soil, followed by rotation backwards as the rear of the Rover proceeds down the ramp. The egress path included a hollow of ~ 10cm depth along the right, clearly seen in the bogie pivot data. The trajectory the Spirit took differed from that measured in test by ~ 5 deg heading, within expectations (Figure 12).

4.3 Opportunity Egress

The smooth terrain of Meridiani Planum was ideal for driving, but estimation of Lander-to-Surface height proved to be the primary challenge. The side-down algorithm during Critical Deploy retracted the airbags more than Spirit, leading to an expectation of higher overall Lander deck heights. Navcam image stereo pairs and geometric camera models are processed [8] to generate a map of 3D range (X,Y,Z) points with an accuracy estimated from test of +/- 5cm (3σ). Featureless terrain combined with lossy compression resulted in poor range maps. Two tactics were employed in response: acquisition of losslessly-

compressed imagery, and rotation of the Lander forward to drive the Egress ramp tips into the soil (Figure 13).

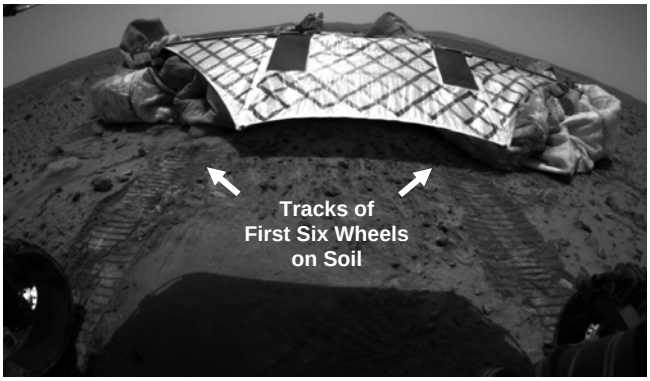

Figure 12 Spirit Egress, Rear View

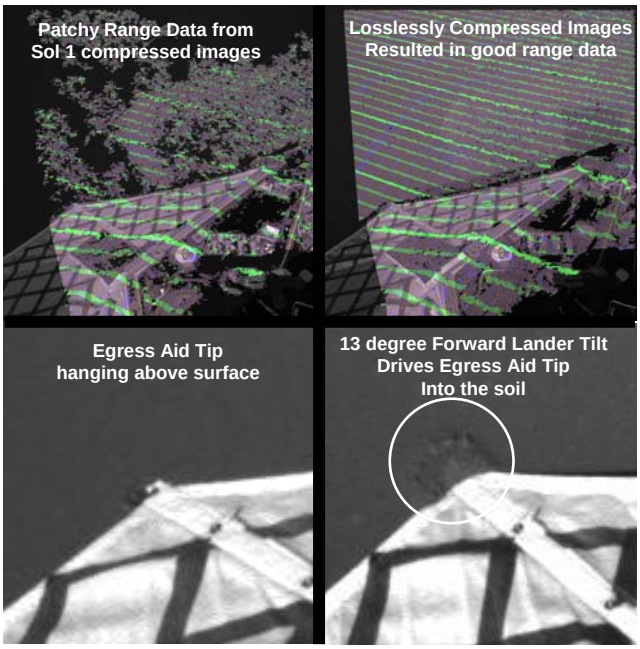

Figure 13 Meridiani challenges deck height estimation

The resulting ~13 degree Lander tilt (Figure 14) served to even out the forward path. A smooth drive achieved twelve wheels on soil, completing the ITE phase. Egress placed the rover within several meters of a rock outcrop that would within weeks provide evidence of past water on Mars.

5 Acknowledgements

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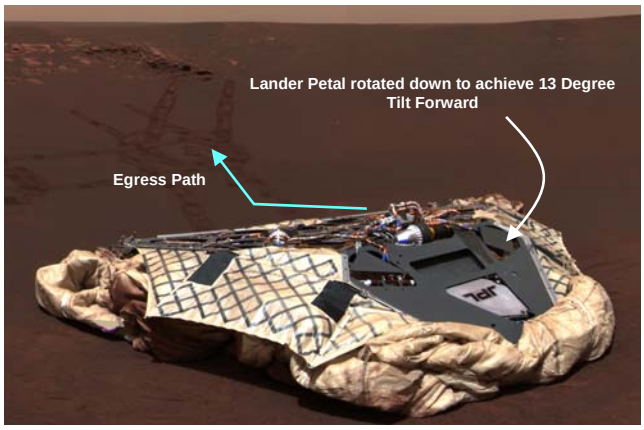

Figure 14 Opportunity Lander Tilted for Egress

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