Mars Exploration Rovers 2004-2013: Evolving Operational Tactics Driven by Aging Robotic Systems

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Over the course of more than 10 years of continuous operations on the Martian surface, the operations team for the Mars Exploration Rovers has encountered and overcome many challenges. The twin rovers, Spirit and Opportunity, designed for a Martian surface mission of three months in duration, far outlived their life expectancy. Spirit explored for six years and Opportunity still operates and, in January 2014, celebrated the 10th anniversary of her landing. As with any machine that far outlives its design life, each rover has experienced a series of failures and degradations attributable to age, use, and environmental exposure. This paper reviews the failures and degradations experienced by the two rovers and the measures taken by the operations team to correct, mitigate, or surmount them to enable continued exploration and discovery.

Nomenclature

APXS	Alpha Particle X-ray Spectrometer
DSN	Deep Space Network
EH&A	Engineering Housekeeping and Accountability
Hazcam	Hazard Camera
HGA	High Gain Antenna
IDD	Instrument Deployment Device
IMU	Inertial Measurement Unit
LSTA	Local Solar Time, Spirit Landing Site
LSTB	Local Solar Time, Opportunity Landing Site
MB	Möessbauer Spectrometer
MER	Mars Exploration Rovers
MGS	Mars Global Surveyor Orbiter
MI	Microscopic Imager
Mini-TES	Mini Thermal Emission Spectrometer
MRO	Mars Reconnaissance Orbiter
Navcam	Navigation Camera
ODY	Mars Odyssey Orbiter
Pancam	Panoramic Camera
PMA	Pancam Mast Assembly
PRT	Platinum Resistance Thermometer
RAT	Rock Abrasion Tool

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SAPP	Surface Attitude Prediction and Pointing
Sol A-#	Spirit Mission Sol Number, beginning January 4, 2004
Sol B-#	Opportunity Mission Sol Number, beginning January 25, 2004

I. Introduction

In January 2004, the Mars Exploration Rovers (MER) project, sponsored by the National Aeronautics and Space Administration (NASA), landed two robotic rovers on the surface of Mars. These twin rovers, named Spirit and Opportunity, were designed and built at the Jet Propulsion Laboratory as robotic geologists, outfitted with tools to examine Martian rocks and soil, and tasked with determining whether water once persisted in the ancient Martian terrain. Each rover was configured as shown in Figure 1, and equipped with a six-wheeled rocker-bogie suspension system to traverse at least 600m from the landing location, carrying resources for independent communications and power generation. The science payload on each rover included a camera mast for characterizing rocks and soils remotely and a robotic arm for in-situ rock and soil measurements. Each camera mast carried a Panoramic Camera (Pancam) for high-resolution imaging through any of thirteen spectral filters, a set of Navigation Cameras (Navcams), and a Mini Thermal Emission Spectrometer (Mini-TES). The robotic arm, called an Instrument Deployment Device (IDD), is a five degree-of-freedom manipulator that deployed an instrument turret with an Alpha Particle X-Ray Spectrometer (APXS), a Mössbauer Spectrometer (MB), a Microscopic Imager (MI), and a Rock Abrasion Tool (RAT) for close-range examination of interesting rocks. Each rover was also equipped with Hazard Cameras (Hazcams) in both the front and rear to view the terrain under the solar array in the vicinity of the wheels. Designed for a 90-sol[a] mission, the equivalent of three Earth months, each rover operated years past her design life. Spirit's mission ended when contact was lost in March of 2010, after a duration of over six years with 7.7 kilometers traversed. Opportunity is still roving today, has traveled over 38 kilometers, and celebrated her 10th anniversary on Mars in January 2014.

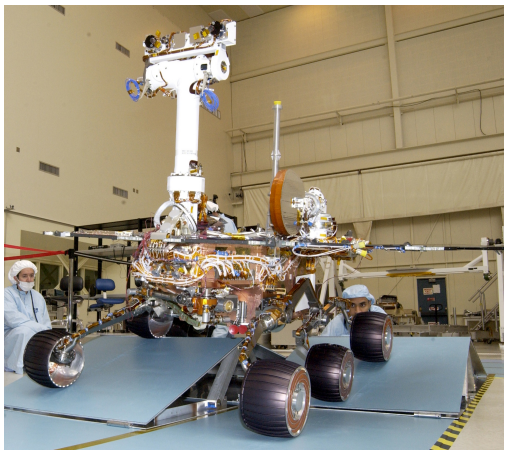


Figure 1. Mars Exploration Rover Spirit during mobility system testing at JPL in 2003. Courtesy NASA/JPL-Caltech.

Over years of exploration and exposure to the harsh Martian environment, both Spirit and Opportunity suffered degradation and loss of hardware capabilities affecting many major rover systems. On both rovers, broken or degraded actuators have affected mobility performance and terrain handling capability. Opportunity has experienced actuator failures and degradation on the IDD and both rovers lost the use of position feedback for their RAT actuators. Dust accumulation has affected solar power generation, as well as camera performance, Mini-TES visibility, and possibly even calibration accuracy for some mechanisms. As years pass, the degradation of instrument energy sources and accumulation of computation errors have grown in significance to materially affect operations. Age, use, and thermal cycling of electronics have taken a toll on switches, sensors, thermostats, and data storage electronics.

Despite the aging and degradation of Spirit and Opportunity, creative operational innovations have kept the rovers surviving, exploring, and discovering. Over the years, a variety of operational strategies have evolved to continue roving without a full complement of drive and steering actuators, to continue in-situ rock analysis without full functionality of the IDD and its toolset, to continue imaging well despite dusty camera lenses, and to continue surviving winters with limited power generation. The success of these strategies is evident in the scientific contributions made by each rover's discoveries, right up to the end of Spirit's mission in 2010, and continuing daily as Opportunity explores the rim of Endeavour Crater.[3] This paper describes the hardware failures and degradations experienced over the course of the Spirit and Opportunity extended missions and the resulting evolution of rover operations to maintain productivity, continue operations, and delay further failure.

[a] A sol is the Martian equivalent of an Earth day, and is 24 hours, 39 minutes, and 35 seconds long.

II. Aging Cameras and Science Instruments

The section that follows discusses the effects of aging and environmental exposure on the instruments of the rover's scientific payload, including effects on both science and engineering cameras. Each of these cameras and instruments played a specific role in scientific evaluation of the Martian surface. As the years passed, some instruments failed and others suffered degraded performance. The operations team applied various approaches for restoring capability, working through or in spite of degradations, or backfilling functionality using another instrument that was still operational.

A. Image Quality Degradation

While constructing, launching, flying, and landing the Mars Exploration Rovers, the team took great care to keep the camera lenses free of dirt and debris. On the Martian surface, however, the lenses are exposed to the elements. Over time, they have collected enough dust to visibly degrade image quality. The accumulated dust on the lenses appears in the images as a mottled pattern, which is most noticeable against areas of uniform texture such as the sky.

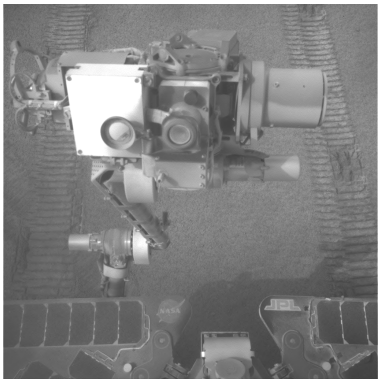


Figure 2. Dust on Opportunity's Microscopic Imager after August 2007.

In general, dust accumulation degrades image quality at a constant rate over time, but there have also been two discrete events that have noticeably increased dust deposition. First, following Opportunity's investigation of her own heat shield on Sol B-344, dust specs were noticed in images from both the Front Hazcam and the MI. Later, the planet-wide dust storm of August 2007 (Sols A-1253 through A-1293 and Sols B-1231 through B-1271) resulted in visible image degradation on the cameras of both rovers. Figure 2 shows an image of the MI taken by the Navcam after the dust storm. Figure 3 compares Front Hazcam images from before and after the dust storm on each rover. In the images collected after the dust storm, the sky appears mottled by dust specs and the overall contrast is reduced. For both Spirit and Opportunity, Navcams, Pancams, and Rear Hazcams all exhibited the same effects.

To mitigate the effects of the dust accumulation, the operations team now periodically collects reference images from the Navcams and MI. These are pictures of the sky pointed away from the sun and generally referred to as "sky flats". These images are used in ground processing to improve the quality of images taken through the dirty lenses. In addition, to improve the signal-to-noise ratio when using the Microscopic Imager, the Opportunity operations team often collects up to three extra images at critical MI positions. The improved image quality provided by these images comes at an operational cost. Collecting them typically requires a factor of 2.5 increase in both acquired data and activity duration. Power and data handling concerns often dictate whether the extra images can be accommodated within a given tactical plan.

B. Degradation and Loss of the Mini-Thermal Emission Spectrometer

Each rover carries a Miniature Thermal Emissions Spectrometer (Mini-TES), a mid-infrared instrument mounted inside the insulated rover chassis that viewed the surrounding terrain through a periscope-like arrangement of mirrors inside the Pancam Mast Assembly (PMA). In surface operations, the Mini-TES enabled remote determination of rock and soil mineralogy, which informed the selection of targets that merited approaching for in-situ investigation. Because the Mini-TES instrument was mounted outside the insulated electronics box, there were concerns that it might be lost before the end of the 90-sol prime mission if dwindling power levels prevented the use of overnight instrument heaters. While winter survival did require the heaters to be disabled, the Mini-TES continued operating nominally for several years.

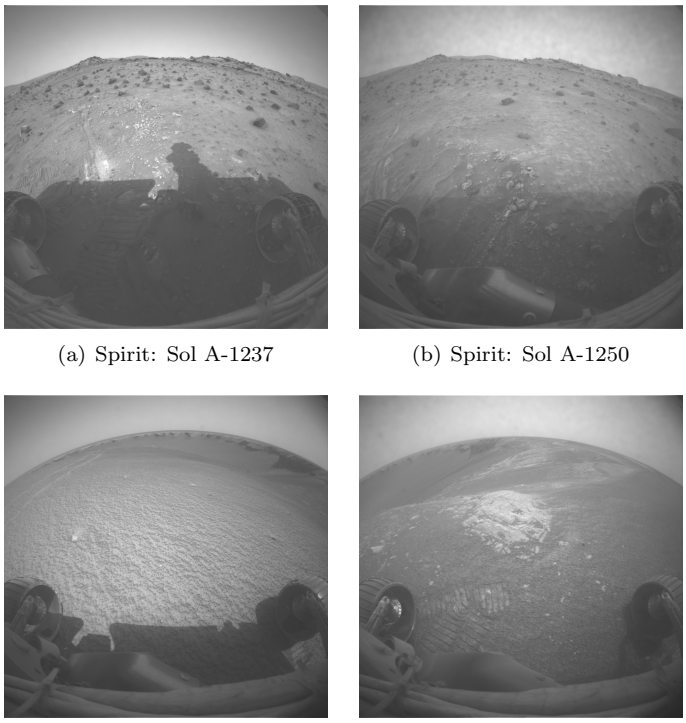
On Sol A-420, the Mini-TES operators for the Spirit rover observed a change in Mini-TES performance. The event coincided with the first major dust-clearing event on Spirit's solar array, and the team concluded that the wind that cleaned Spirit's solar cells had also blown dust onto the Mini-TES mirrors. Over the next few years, occasional events added more dust to the mirrors, but the science team, with careful calibration, continued to glean useful data from the instrument in spite of the dust effects.

In August 2007, the same planet-encircling dust storm that dirtied the camera lenses significantly increased the dust opacity on the Mini-TES mirrors. On Spirit, the dust obscured approximately 80% of the

instrument's signal. For Opportunity, the dust coating was sufficiently thick that the signal was completely obscured. Because the Mini-TES signal suggested no external terrain was in view, on Sol B-1288, operators pointed the MI at the Mini-TES mirror opening in the PMA and used imagery to verify that the mirror was opening and closing as commanded. Several attempts were made to remove the dust from Opportunity's Mini-TES mirrors. On Sols B-1680 and B-1705, the team attempted to shake off the dust by vibrating the mirror attached to the actuated shroud. Beginning on sol B-1913, operators opened the Mini-TES mirror overnight, hoping for a wind-induced cleaning event similar to those experienced on the solar panels. Neither of these methods resulted in any noticeable improvement.

On Sol B-2250 the Opportunity Mini-TES began showing signs of a fault in its control electronics. The instrument exhibited various problems with data collection and seemed unable to successfully coordinate measurements with PMA pointing locations. After several unsuccessful attempts to diagnose the problem, Opportunity's Mini-TES instrument was finally declared lost on Sol B-2709. Spirit's Mini-TES, while dusty, continued returning data until her final winter shutdown in March 2010.

Loss of the Mini-TES instrument affected the ability of the operations team to remotely evaluate the mineralogy of rock and soil targets. Fortunately, the team scientists have developed an alternate means of identifying rocks and soils with desirable mineralogy for in-situ investigation. Using Pancam imagery with specific spectral filtering, the hydration signature of materials can be evaluated remotely.[9]



(a) Spirit: Sol A-1237 (b) Spirit: Sol A-1250

(c) Opportunity: Sol B-1206 (d) Opportunity: Sol B-1273

Figure 3. A comparison of Front Hazcam images from Spirit and Opportunity before and after the planet-wide dust storm of August 2007.

C. Degradation of the MB Source

The Mössbauer spectrometer was used to detect iron-bearing minerals in the Martian rocks and soil when placed in contact with a target by the IDD. Central to the operation of the MB was a small amount of Cobalt-57, a radioactive isotope with a half-life of 271 days. At the beginning of the mission, collecting a quality MB spectrum required the instrument to be placed on a target for 8 hours of integration time. By mid 2007, five half-lives later, quality MB measurements required integration times of about 48 hours.[4] As more half-lives passed, the sources grew weaker and integrations grew longer until acquiring MB measurements was no longer feasible. The last MB measurement collected by Spirit was on the soil target Thoosa for almost 207 hours on Sols A-2052 through A-2063. Opportunity's last MB integration was on target Amboy on Sols B-2852 through B-2892, and anomalous signals were reported throughout the integration campaign, suggesting that the instrument itself had experienced some functional degradation.

Although the Mössbauer Spectrometers are no longer used for reading mineralogy, the MB is the first instrument Opportunity places on the surface of most in-situ science targets. The contact switch at the end of the MB is the most reliable tool for accurate surface detection and is used to ensure accurate placement of the RAT, MI, and APXS instruments.

D. Unreliable APXS Door Latch

The Alpha Particle X-Ray Spectrometer (APXS) is an in-situ instrument which detects the elemental makeup of a rock or soil when placed in contact with a target by the IDD. To protect the instrument from dust accumulation, the APXS was designed with a pair of doors that open and close to cover the sensor between

in-situ readings. A contact ring around the rim of the instrument opened the doors when pressed against a hard surface and caused the doors to latch in the open position. After observations, the doors were closed by rotating the turret of the IDD to a pose designed to release the latch.

From the beginning of the surface mission the APXS doors and contact ring proved difficult to use. The forces on the contact ring needed to be evenly distributed around the ring to get both latches to engage. As rock surfaces tend to be rough, it was difficult to ensure that the doors were opened adequately to take a measurement. To avoid uncertainty, on Sol B-105, the operations team began routinely using the APXS calibration target as a known level surface upon which to open the dust doors.

However, on Sol B-161, the APXS doors failed to latch, despite performing the opening procedure on the calibration target surface and an indication of successful contact from the associated limit switches. The suspected cause of the latch failure was mechanical fatigue in the door latch mechanism. Because mechanical failure of the door latch would prevent subsequent use of the APXS for target chemistry, the team chose to discontinue closing APXS dust doors on both rovers. To avoid accidentally closing the doors, the software limit for the IDD turret joint was adjusted to exclude the pose at which the APXS doors release.

Over 3000 Sols later, the APXS instrument continues to return useful data, despite being left open to potential dust deposition. In fact, leaving the doors open has enabled frequent APXS measurements of argon in the atmosphere from the IDD's stowed position.

E. Rock Abrasion Tool Bit Wear

The Rock Abrasion Tool (RAT) grinds away the weathered surface of Martian rocks, enabling measurement of the rock's unweathered makeup. The rock is ground away by a cutting bit, which is pressed against the rock surface and rotated at high speed. The cutting bit is made of a diamond-impregnated epoxy matrix which is expected to wear away with use and was designed for abrasion of three rocks as specified in the mission success criteria. On Sol A-496, an attempt to grind with the RAT failed, with chatter in the contact switch that suggested the bits had been bouncing off the rock rather than grinding it away. Investigation concluded that Spirit's RAT bits had been worn out and that grinding with the Spirit RAT was no longer feasible. From that point on, the Spirit RAT was used only for brushing surface dirt from rock targets.

The loss of RAT grinding capabilities on Spirit alerted the team to the limited life of the RAT bits, and caused the operations team to start tracking the use of Opportunity's RAT bits as an exhaustible resource. To reduce bit wear, IDD preload for RAT activities was limited to 40 N, and RAT grind activities were limited to only high priority targets approved by the Principal Investigator. After each grind, the RAT bits are imaged and assessed for the level of wear and expected remaining life. At the time of this writing, approximately 25% of Opportunity's RAT bit material remains.

F. Camera Elevation Pointing Inaccuracy

To achieve accurate colors in images collected by the Pancam, the MER team uses images of a calibration target (caltarget) mounted on each rover's deck to adjust for the effects of airborne dust and varying lighting conditions. Although identical positioning commands are used to point the camera at the caltarget for each observation, the accumulated images from several years of operations showed the caltarget gradually drifting upward within the frame. It was apparent that the camera pointing error was steadily increasing.

Upon further investigation, the team also noted sudden reductions in the pointing error, and were able to correlate the camera pointing changes with the observed cycle of dust deposition and dust cleaning events on the rovers' solar arrays. The team believes that the observed caltarget pointing variation can be attributed to gradual dust deposition and sudden cleaning events on the hardstop for the camera mast actuators. Thus far, the pointing errors have never grown large enough to require any operational mitigation.

III. Aging Mechanisms

One of the wonders of the Mars Exploration Rovers mission is the continuing functionality of dozens of actuated mechanical systems. Opportunity's actuators have now operated through over 40 times the primary mission duration and have survived over 3600 Martian thermal cycles. Over 10 years of operations, only a few mechanisms have failed, and the team has been fortunate that none of these have fully immobilized the mission or fully disabled any critical rover function. The following section describes each mechanism that

has partially or fully failed and the measures taken by the operations team to remain mobile and productive despite these failures.

A. Loss of Spirit Wheel Drive Actuators

As Spirit traversed the three kilometers from Bonneville Crater to the Columbia Hills between Sols A-86 and A-156, the current draw of the rover's right front wheel exhibited a significant increase relative to the other wheels. From a typical wheel current of approximately 0.4 Amps during driving operations, Spirit's right front wheel current draw had increased to nearly 1 Amp, with an exponential increase over the the last 10 drives of the traverse. The suspected cause was poor distribution of lubricant within the actuator. Without intervention, failure of the drive motor was expected to occur within the next 100 meters. For the subsequent 200 Sols, the team adopted a strategy of driving Spirit backward with limited actuation of the right front wheel. This strategy, along with additional heating of the mobility system prior to driving and long stops for in-situ science activities, returned the current draw on Spirit's right front wheel actuator to nominal levels, and nominal Spirit mobility operations resumed.[6]

For the next year, Spirit continued traversing nominally. Occasional transient current spikes of over 1 Amp ware observed on the right front wheel, but there was no trend of rising current draw overall. In March of 2006, these transient spikes began occurring more frequently, and were seen on three consecutive drives on Sols A-768, A-772, and A-774. On Sol 779, Spirit's right front wheel stalled. Subsequent diagnostics suggested an open or near-open control circuit to the wheel actuator.

With the right front wheel immobilized, traversing with the Spirit rover became very challenging. The wheel, locked in position, reduced the effective thrust generated by the mobility system by approximately 17%. In addition, the rocker-bogie suspension system, which so effectively balanced wheel loading under nominal conditions, continued to distribute rover weight onto the stuck wheel causing it to plow through surface material with the wheel cleats catching on the terrain, digging a trench as shown in Figure 4. Together, these effects reduced the drive speed of the rover and significantly reduced the steepness of incline that Spirit could climb. The asymmetry in the thrust produced by the mobility system caused Spirit to drift and yaw to the right when driving. The amount of course deviation depended significantly on the terrain roughness and slope.

Figure 4. Bright soil exposed in the trench created by dragging Spirit's failed right front wheel.

Through experimentation in both the testbed and on Mars, the team learned that the remaining wheels would pull the broken wheel more easily over rocks and uphill when driving backward. Several methods were developed to compensate for rightward drift, which was reduced, but not eliminated, when driving backward. In general, accurate traversing required frequent checks of onboard heading and progress knowledge, made accurate by tracking Spirit's slipped position using visual odometry[5] and slipped heading as sensed by the Inertial Measurement Unit (IMU). Command sequences were built with many conditional branches, enabling real time course corrections.

While backward driving produced the highest accuracy and efficiency for 5-wheeled traverse, short forward drives were often desired, particularly when attempting to approach rock targets for in-situ science with the IDD. Course correction tactics used for backward driving sometimes lacked sufficient precision for approaching an in-situ target. To proceed along a relatively straight trajectory, the team developed a method to counteract pivoting about the right front wheel. Steering the rear wheels slightly to the right created a leftward pivot, countering the rightward pivot of the stuck wheel. This tactic made slow progress and put additional stress on the wheels and suspension, but was suitable for short-distance drives, and in conjunction with visual odometry and conditional sequencing enabled Spirit to reach targets successfully.

These measures enabled Spirit to continue to traverse and approach rock targets, though at a significantly reduced rate of progress. Wheel-dragging reduced the traverse rate, and visual odometry processing times slowed progress further. In addition, the increased friction produced by the stuck wheel resulted in frequent

difficulties. Spirit's right bogie frequently "popped a wheelie", swinging the rear wheel off the ground and reducing the number of productive wheels to four. The rover was also more easily bogged down in soft terrain. Sand traps sometimes required the use of differential drive speeds. When one side of the rover was unable to produce traction, the wheels with purchase were driven faster, propelling the rover, while the other side was driven slowly to avoid further embedding without acting as anchors.

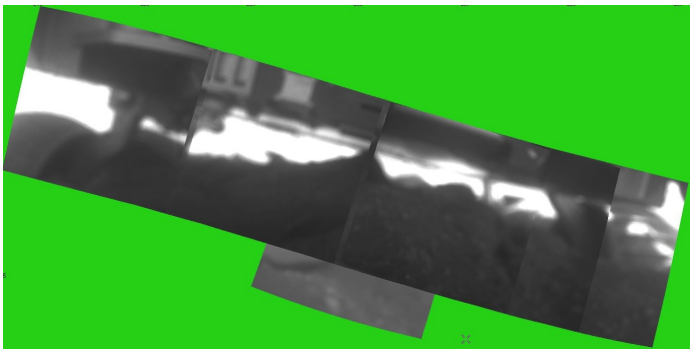


Figure 5. Panoramic view underneath the Spirit rover using the Microscopic Imager.

In April 2009, on Sol A-1886, Spirit's left wheels broke through a surface crust that had concealed a bowl of soft dust in a small crater. This left only the two functional right wheels with the ability to provide much thrust. In the cohesionless soil, familiar methods failed to produce motion in any direction, and the rover embedded more and more deeply with each attempt. As the wheels sank, reducing the ground clearance of the rover chassis, the team grew concerned that Spirit would become high-centered on a protruding rock. Using the MI, the operations team began collecting periodic panoramas of the terrain under the rover. Figure 5 shows one of these panoramas, in which the fuzzy appearance is due to the MI fixed focal length, designed for imaging at just a few centimeters away from its target. The operations team used these images to monitor both the rocks under Spirit's belly and the embedding of the middle wheels, which are not easily viewed by any other camera.

During the extraction attempt on Sol A-2092, the right rear wheel stalled. This wheel ultimately failed just a few sols later. With five wheels fully buried and only four functioning, a new driving technique was developed. Because the steering axes are not centered within the wheels, the wheels do not turn on a point when steered. Coordinated steering the submerged wheels pushed Spirit incrementally backward. This, alternated with driving the functional wheels to redistribute the soil, resulted in a few centimeters of backward progress on each sol of driving. Unfortunately, before extrication was complete, winter set in and the power levels no longer supported mobility.

B. High Currents on Opportunity Drive Actuator

Around Sol B-151, the right front wheel actuator on the Opportunity rover started drawing erratic currents when driven. This observation coincided with the mitigation process for the elevated currents on Spirit's right front wheel, and the same root cause was suspected: loss of lubrication in the wheel actuator. However, as no trend was seen toward overall elevated current levels, no corrective action was taken.

Nominal driving continued for over two years. Then Opportunity operators observed increasing current draw on the right front wheel over the course of eight drives between Sols B-1089 and B-1105. By this time, Spirit's right front wheel had failed entirely. In an attempt to redistribute lubricant through the actuator, the team began aggressively heating the right mobility actuators before each drive, to 0°C rather than −20°C. In addition, all traverses were executed in a backwards direction. After five traverse sols and a "rest" stop for in-situ science with the IDD, the right front wheel currents had returned to nominal levels.

In the years that followed, Opportunity's right front wheel occasionally showed rising current levels, particularly in the execution of long traverse campaigns. Whenever one of these episodes was detected, the team "rested" the wheel, standing down from mobility for several sols, preferably with the right front wheel exposed to the sun. The heaters were used frequently to further warm the right mobility actuators. When mobility resumed, all planned drives were of limited distance and executed backward until nominal current levels were observed on the right front wheel. During the years spent traversing from Victoria Crater to Endeavour Crater, Opportunity drove almost exclusively backward. Around Sol B-1675, the team again raised the heating target for drive activities. Before any drive, the right mobility actuators were required to reach a preheat temperature of 10°C. These measures were very effective. Though Opportunity continued to experience occasional elevated currents on her right front wheel, no persisting trend toward poorer performance has ever emerged.

Until recently, Opportunity has primarily traversed terrain ranging from soft sandy dunes to flat hard

packed soil and broken slabs of flat outcrop. Today, Opportunity primarily traverses sloped terrain on the rim of Endeavor Crater, and in this new environment, a new pattern of behavior has emerged. When traversing slopes, the loading conditions on the right front wheel appear to have more influence on current draw than does the selection of drive direction. As Figure 6 illustrates, currents are highest on the right front wheel when the wheel is downhill and carrying a larger percentage of the rover's weight. When the right front wheel is uphill and less heavily loaded, currents are lower. This pattern appears to apply regardless of whether drives are executed in the forward or backward direction.

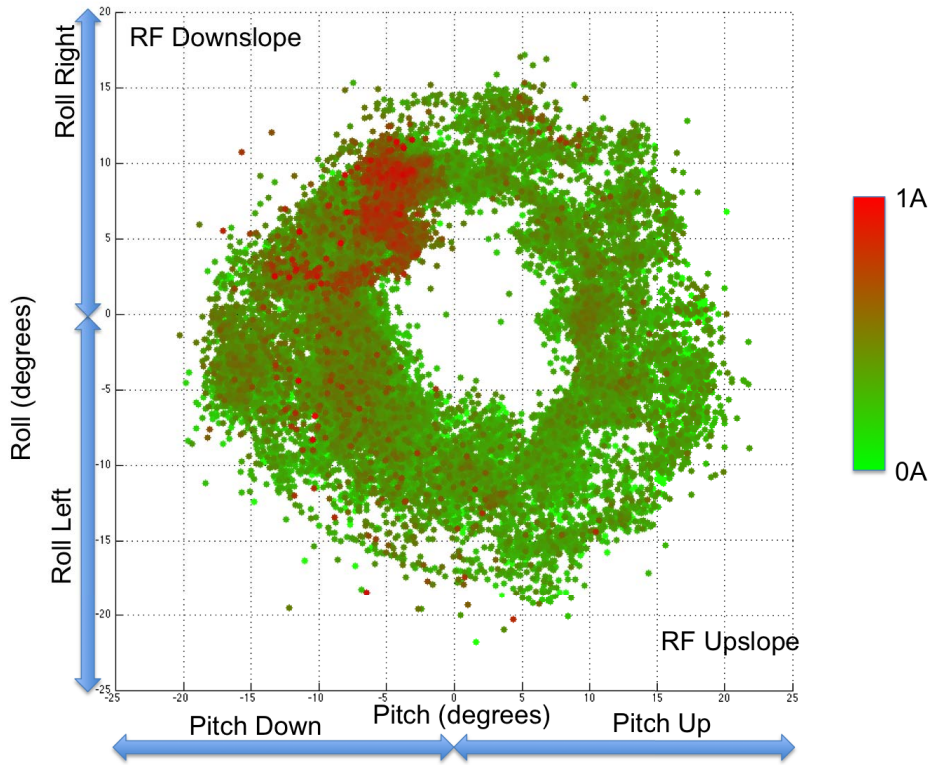


Figure 6. Variation in current draw by Opportunity's right front wheel correlated with rover attitude. Data is for drives at Solander Point, 2013-2014, where traverse slopes were typically 5 degrees or more.

C. Loss of Opportunity Steering Actuator

Opportunity's right-front wheel steering actuator failed on Sol B-443, less than one Martian year into the mission. An anomaly investigation team concluded that the likely cause was a physical obstruction in the first planetary stage of the actuator.[6] The failure left the right-front wheel toed in at about seven degrees. As a result of this steering position, when driving straight ahead, the right front wheel tends to creep to the left. This tends to push the front of the rover to the left and out of line with the planned path. It also tends to push the front wheels toward each other. This puts some level of stress on the mechanical components and on the drive actuators for the right front wheel. Fortunately, the additional stress is relatively benign, though it may contribute to occasional elevated current levels on the right front drive motor.

One of the consequences of the frozen actuator was a reduction in precision for approaching a target for in-situ science investigation. Three general approaches are taken to mitigate this. The primary method approaches by driving forward while using visual odometry to measure the effect of the toed-in wheel and to compensate with a final turn to the desired target to place it in the IDD work volume. The final turn uses the IMU while turning to make sure the rover turns the appropriate amount. Since the unsteered wheel will not contribute equally to the turn, the other wheels force the rover to the correct heading based on the IMU output. Alternatives that are used occasionally include driving backwards over the target to bring it into the work volume while reducing the effect of the loss of steering and approaching along a curved arc where the steering for the arc matches the permanent steering angle of the right-front actuator. This corresponds

to a heading change of about 11 degrees counter-clockwise for each meter driven in the forward direction

When driving forward or backward, the right front wheel steering angle is very close to nominal. For turns in place, on the other hand, the four steerable wheels are nominally steered inward to rotate the rover. Now, the failed actuator prevents Opportunity's right front wheel from reaching the correct position, and it generates thrust at a significant offset to the path of the other five wheels. As a result, during turns, soil accumulates against the inside or outside of the right front wheel, resisting motion and putting additional stress on the suspension system. To prevent damage to the wheel or suspension, the operations team now avoids very large turns in place and instead executes large heading changes via three-point turns or "spirograph" turns in which small turn segments are separated by short forward or backward drive segments that move the wheel away from the accumulated soil.

The sideways motion of the right front wheel during point turns also increases the risk that a rock could be scooped into the wheel's interior. Not all scooped rocks are dangerous, but rocks of a certain size have the potential to jam against the internal wheel hub, preventing further wheel rotation. The risk is greatest when traversing in rock-bearing material soft enough for partial wheel embedding, the conditions in which a rock stalled Spirit's right rear wheel on Sol A-339. In that case, the rock was eliminated by steering the wheel to a position that allowed gravity to draw the rock out in the downhill direction. With a stuck steering actuator, that solution is not available for Opportunity. Fortunately, much of the terrain traversed by Opportunity has been either sandy and devoid of rocks or rocky over a terrain of firm bedrock outcrop.

D. Opportunity Steering Actuator Position Drift

The positions of the steering actuators on Opportunity's front and rear wheels are tracked by two independent devices. The first measurement instrument is an incremental encoder, which provides information about the motion of the actuator. This sensor has no absolute knowledge of position but measures the relative motion of the actuator with high precision. Absolute steering position is calculated by tracking the number of encoder counts relative to a calibrated hard stop. The second measurement device is a potentiometer, a variable resistor which returns a different resistance value at each position of the actuator. Unlike the encoder, this device provides an absolute position measurement without the need for additional processing.

Over the course of Opportunity's exploration, the position values returned by the encoders and potentiometers on her steering actuators have drifted apart. Figure 7 plots the difference between the encoder and potentiometer position measurements for each steering actuator over the course of the mission. The data set for Figure 7 contains one correlated potentiometer and encoder reading per sol, typically at a time with no mobility actuation. The spike in the plot at sol B-201 represents a data point sampled while the mobility actuators were in use.

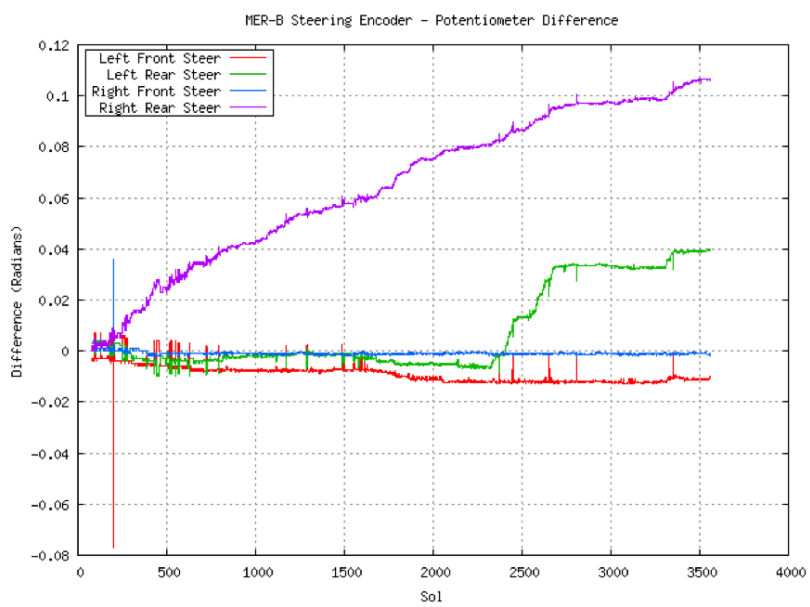


Figure 7. Angular difference between encoders and potentiometers on Opportunity Steering Actuators for Sols B-1 through B-3600

The two rear steering actuators have the largest measurement discrepancies between the potentiometer and encoder. The right rear steering position has been steadily drifting since near the beginning of the mission while the left rear steering began to drift significantly around Sol B-2400. Increases in encoder-potentiometer measurement discrepancy tend to correspond with periods of heavy actuator use. The right front steering actuator for Opportunity has shown no measurable drift since Sol B-433, when the steering actuator jammed.

A large difference between the encoder and potentiometer readings is not expected under normal conditions. The disparity between these readings indicates that the encoder, potentiometer, or both devices are deviating. The operations team is not currently able to determine which device is faulty from the available data, however, driving and steering appear unaffected.

Since the rover uses encoder-derived measurements to determine the stopping position of the steering actuator, an error in this measurement negatively impacts traverse accuracy. Moreover, if the encoder measurement is drifting, it is possible that the steering actuator could make unexpected contact with its hard stop while turning to the turn-in-place steering angle. While this concern is legitimate if the encoder-potentiometer drift continues to increase, the current maximum measurement divergence remains comfortably below the margin between nominal operational steering positions and the hard stop location. Even if the hard stop were reached, the actuator would most likely stall but continue to function nominally thereafter. If the measurement error resides in the potentiometer, there is no impact to the rover except in a case of encoder failure.

Presently, the encoder-potentiometer measurement drift poses no imminent problem to the rover, so no operational workarounds have been necessary.

E. Loss of IDD Shoulder Azimuth Actuator

On Sol B-654, the shoulder azimuth actuator on Opportunity's IDD stalled while attempting to deploy the arm. Extensive testing and investigation by an anomaly team concluded that one of the two motor windings in the actuator had developed an open wire. This failure was attributed to extreme thermal cycling caused by a stuck heater switch that resulted in overheating of Opportunity's IDD shoulder azimuth and elevation actuators. It was expected that continued thermal cycling might eventually open a second motor winding, resulting in complete failure of the shoulder azimuth actuator. Because loss of the shoulder azimuth actuator would prevent IDD deployment from the below the rover chassis, the operations team adopted a policy of keeping the IDD unstowed except during mobility operations. In the case of total shoulder azimuth failure, a deployed IDD could continue placement of the in-situ science instruments using the remaining four joints.[6]

For Sols B-731 through B-1499 the Opportunity IDD was stowed before each mobility activity, then immediately deployed when the mobility activity completed. Occasionally, mobility activities were aborted due to intermittent shoulder azimuth failures while stowing the IDD. On Sol B-1502, the shoulder azimuth stalled with a signature that suggested the actuator had experienced a secondary failure. On Sol B-1538 an attempt was made to move the shoulder azimuth. The motion command resulted in a small position change, but ended in a motor stall. Since Sol B-1538, no further shoulder azimuth motion has been attempted.

1. Opportunity IDD Pose for Traverse Activities

To continue traversing without risking loss of the arm and its instruments, a new traverse pose for the IDD was needed. The operations team began researching IDD poses that would enable the arm to remain deployed while driving without endangering the remaining functional actuators and instruments. Without the mechanical latching points of the standard stow position, loss of IDD joint calibration was also a concern.

The first evaluated pose positioned the IDD turret in a hovering position above the front solar panel. This position was nicknamed the"hover stow" or the "thinker stow", after the famous "Le Pensure" statue by the artist Auguste Rodin, and was tested by Opportunity on Sols B-706 and B-717. Analysis and testing suggested this pose could tolerate terrain discontinuities up to about 4 cm. Because Opportunity often traverses areas with rocks and ledges greater than 4 cm in height, this pose was not adopted as a permanent solution.

The pose shown in Figure 8(a) is the current standard, and was developed to minimize torque on the four functional IDD joints. The shoulder elevation joint holds the IDD mass as close as possible to the rover while leaving a safe margin between the upper arm link and the solar array. The elbow angle places the turret directly below the elbow joint at the position of lowest potential energy. The wrist angle positions the turret parallel to the terrain for maximum clearance while traversing. The turret angle points the Mössbauer contact plate toward the Front Hazcams such that the circular geometry of the contact plate can be easily imaged by both cameras. This IDD configuration resembles a fishing rod with a line and is typically referred to as the "Fishing Stow".

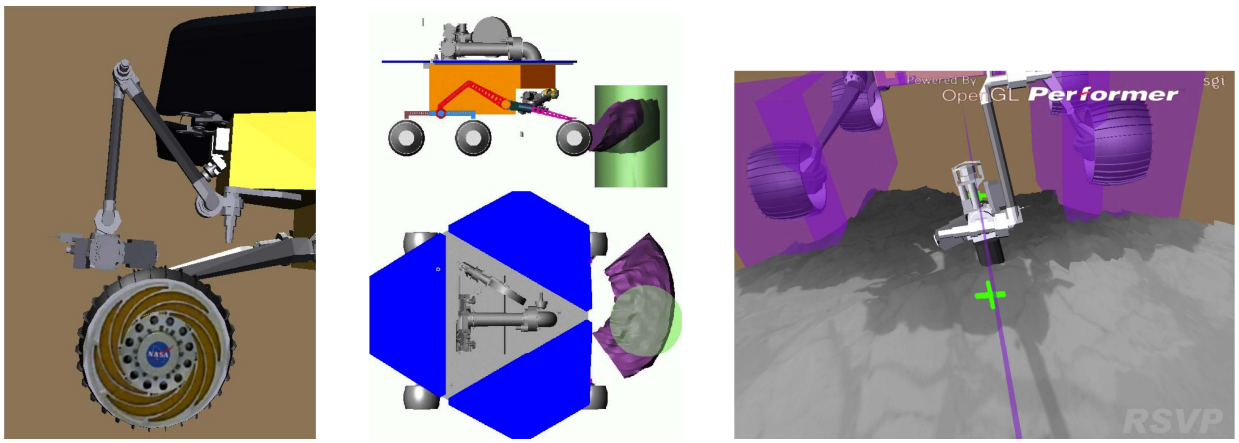
The "Fishing Stow" was first tested on the Martian surface on Sol B-1531. After each drive, the contact plate is used as a fiducial for machine vision algorithms that compare the current pose to a reference pose

imaged on Sol B-1544 and check for undetected IDD position changes that could signal a loss of calibration due to driving loads.

2. *Effects on In-Situ Science*

The loss of Opportunity's shoulder azimuth joint significantly affected the rover's workspace for placement of the in-situ science instruments. With only four functional joints on the IDD, the arm workspace was reduced to a plane intersecting the terrain in front of the rover. Figures 8(b) and 8(c) show the nominal workspace before the joint failure and the limited workspace that remained afterward.

This reduced workspace, referred to now as the "IDD Workplane", limits the flexibility of target selection for in-situ instrument placement. Approaching an in-situ target requires a much higher level of accuracy in mobility planning and execution. For targets of small diameter, achieving the required precision in workplane placement often requires multiple sols of position refinement.



(a) Opportunity IDD "Fishing Stow" pose

(b) Nominal IDD workspace, shown by the green cylinder.

(c) Opportunity IDD workspace after shoulder azimuth failure, shown by the purple line.

Figure 8. Opportunity IDD "Fishing Stow" and reduced workspace after the loss of the shoulder aziumuth joint.

F. Faulty Potentiometer in IDD Elbow Joint

After the failure of the shoulder azimuth joint on the IDD, an autonomous stow check was enabled to detect untracked IDD motion while driving. Several times each second, the potentiometer-based positions of the five IDD joint angles are measured and compared to the expected joint angles for the "Fishing Stow" configuration.

When using the stow check, the position of each enabled joint is compared to the desired position. Due to shared channels on the motor control board between actuators, it is not possible to monitor the IDD joint encoders while driving. For this reason, joint angles for the stow check are determined from each joint's potentiometer readings. If the measured position is outside a parameterized tolerance, an error is declared, and drive motion is halted.

Stow checking for the wrist and turret joints carries a high likelihood of false positive errors due to backlash in those joints that would be tracked by the potentiometer but not the encoder. For this reason, the stow check for both wrist and turret remains disabled. The shoulder elevation and elbow actuators have very little backlash, making them less susceptible to motion induced by mobility loads.

On Sol B-3349, Opportunity's drive was stopped due the elbow joint potentiometer indicating that the joint had rotated 2.5° outside the acceptable range of stow angles. This value was transient and after drive motion had stopped, the potentiometer value indicated that the elbow joint was at an acceptable stow angle.

Similarly, the drive on Sol B-3350 did not execute as the elbow joint potentiometer once again reported the elbow joint to be outside the stowed position. In this instance, the potentiometer indicated that the elbow joint was 22.5° from an acceptable stow angle. Diagnostics of the elbow joint showed that the joint was operating nominally and had not moved.

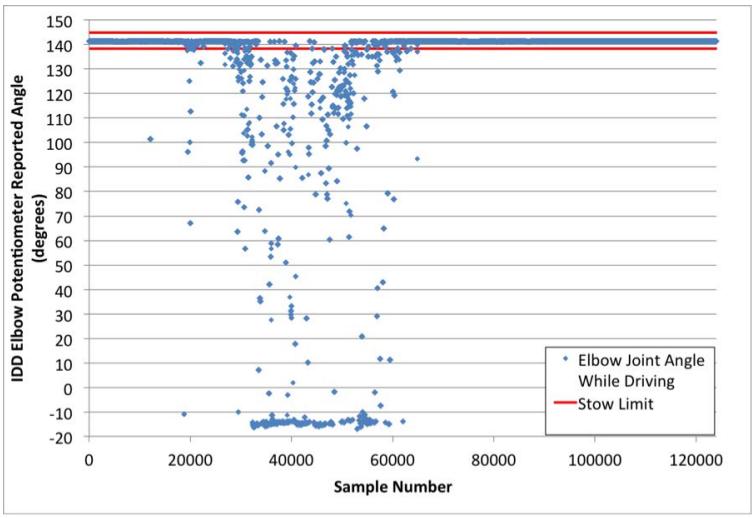


Figure 9. Opportunity elbow potentiometer readings while driving, Sols B-3345 through B-3545.

The two drives that were stopped by the IDD stow check came at a time when Opportunity was driving between Cape York and Solander Point on the rim of Endeavour Crater. Opportunity needed to traverse this distance expeditiously in order to reach favorable tilts for the next Martian winter. After analysis indicated that the elbow joint potentiometer readings were erroneous, stow checking for the elbow joint was disabled. Subsequent drives executed nominally and were not stopped despite the potentiometer at times indicating that the elbow joint was as much as 154° outside the acceptable stow range. Figure 9 shows the elbow joint angle sampled while driving between Sols B-3345 and B-3545.

There are several possible causes for the erroneous values reported by the elbow potentiometer. The first possible explanation is contamination on the potentiometer. Debris may have collected where the potentiometer wiper contacts the resistive element when the elbow joint is in the "Fishing Stow" position. The elbow joint is not often rotated beyond the "Fishing Stow" angle. Elbow joint diagnostics performed on Sol B-3351 moved the elbow joint to an angle of 157°. These diagnostics did not identify the cause of the erroneous readings or clear any putative debris.

The second possible explanation is that small motions of the elbow joint while driving have caused wear at a specific location on the potentiometer causing erroneous readings. The return to nominal values may be explained by high pitch components of tilt. The small amount of backlash in the elbow joint may be causing the potentiometer to be sensing on a less worn area. Likewise the small motions may over time have been able to move possible debris.

The final possible cause is the potentiometer itself. The potentiometers used on the MER rovers are not designed for use in low-pressure environments. The Martian atmosphere pressure is on average around 6 mbar.

To militate against future drives being prematurely stopped, stow checking of the IDD elbow joint while driving remains disabled. If a root cause is successfully determined and can be mitigated, stow checking may be re-enabled at that time.

G. Loss of Encoders on RAT Actuators

On Sol B-1045, the grind motor on Opportunity's RAT stalled during its pre-activity calibration cycle. Investigation showed that the motor still functioned, but its encoder data no longer updated with motion of the motor shaft. The RAT uses three motors; the grind motor spins the cutting bits and cleaning brush, the revolve motor moves the spinning bits and brush in the cutting plane to abrade a circular patch, and the z extension motor advances the cutting plane to achieve the desired abrasion depth. Without encoder feedback, the RAT grind motor could be controlled only in an open-loop fashion using low-level commands designed for motor testing. Using the Surface System Test Bed, a set of sequences was created to implement all necessary RAT behaviors while running the grind motor in open-loop. Deployment of this solution on the Martian surface also required a patch to rover software to eliminate safety checking that relied on the failed encoder.

On Sol A-1341, Spirit's RAT grind motor failed with the same signature as Opportunity's. Functionality was restored quickly using the workarounds already in use for RAT activities on Opportunity.

Just two weeks later, on Sol B-1334, the encoder on Opportunity's RAT revolve motor failed. Using open-loop motor commanding to control both the grind and revolve motors required a more complex recovery effort. Because RAT performance is sensitive to the revolve speed, diagnostics were run on Mars to measure the speed of revolve motor rotation when run at different open-loop voltages. The speed-voltage relationship was temperature dependent, requiring small adjustments to the voltage levels for activities at different times

of day or during different seasons. In addition, the motion of the revolve and grind motors had to be properly coordinated to obtain nominal results. The software behaviors designed and tested to coordinate these motions and perform the associated safety checks relied on the encoders and was no longer usable. The basic functionality of these software behaviors was recreated in open-loop command sequences and carefully vetted in the testbed.

The initial deployment of the new workaround to tactical surface operations appeared at first to have gone well. However, the team soon noticed that the RAT brush was exhibiting unexpected behavior. A typographical error in RAT documentation had mislead the tactical team, and the grind motor had been run in the wrong direction, bending the metal bristles of the cleaning brush. Fortunately, the bent brush continued to perform well enough for good results in subsequent operations, though a little pile of dust tends to get left behind in the very center of the RAT grind surface after cleaning.

The three encoder failures followed a pattern that suggested a possible root cause. In the flex cable that carries motor control signals to the RAT down the length of the IDD, encoder signals are arrayed on one side. The grind motor's encoder connections are closest to the edge, then the revolve motor's encoder connections, then the encoder connections for the RAT z extension motor. It seemed likely that damage to the cable was slowly breaking the connections deeper and deeper into the cable, and the RAT z extension encoder would likely be next.

The encoder for Opportunity's RAT z extension motor failed on Sol B-1759, further supporting the hypothesis that degraded flex cabling was at fault. The operations team went back to the testbed and developed the most involved set of inter-related sequences that has been approved for use on Mars. While the revolve and grind motors are run in open-loop, a parallel command sequence handles open-loop control of the z extension, pressing the bits downward in minuscule increments with timing correlated to the speed of the open-loop revolve.

At the time of this writing, the Opportunity operations team continues to grind and brush surfaces with the RAT using the open-loop sequence set. It is expected that the flex cable continues to degrade with continued IDD use. Fortunately, several spare connections isolate the motor control connections for the RAT z extension motor from the encoder connections that are known to have failed. Hopefully, these connections will remain intact and enable RAT use for the remainder of Opportunity's mission.

H. Loss of Dynamic Brake Sensing

Many rover actuators use a dynamic brake system to hold position when the actuator is uncontrolled. A dynamic brake uses electrical traction to prevent components from moving. The dynamic brake relays are active relays meaning that their default state is closed. When power is removed from the relay, the relay closes and the brake is enabled, resisting actuator motion. A sense line is mechanically attached to the relays and it senses if relays are opened or closed. A fuse is also placed in series with the relay in order to control the applied current. In a nominal case, when actuator motion is commanded, the relays open, disabling the dynamic break. Before the motion is initiated, the sense line is checked to verify that the relays are open.

The actuators also include magnetic detents, which independently resist motion. The magnetic detents resist rotational motion using magnetic attraction while the motors are quiescent. When a motor is energized, the magnetic field generated by the motor coils overpowers the detent force. Alongside the magnetic detents, the dynamic brake provides redundancy to ensure that actuator position is stable, even under dynamic loading experienced during rover traverse.

On Sol A-265, mobility activities failed when the status check on the dynamic brake state for Spirit's right front and left rear steering actuators indicated that the brake had not opened for a commanded motion. Analysis and testing indicated that the probable root cause of the dynamic brake anomaly was the buildup of "wear polymer" on the sense line contact, leading to inaccurate sensing of the dynamic brake state. To return the affected actuators to service, rover software was configured to ignore the dynamic brake state when commanding Spirit's right front and left rear steering actuators.

A mobility failure with the same signature occurred on Sol A-733 when attempting to move Spirit's right rear and left front steering actuators. Diagnostics indicated the same root cause. The dynamic brake functioned but its state was incorrectly sensed. The same operational solution was applied.

Spirit's High Gain Antenna (HGA) gimbal experienced the same dynamic brake sensing failure on Sol A-2027. Recovery mirrored the procedure used for the steering actuators, configuring software to ignore the dynamic brake state.

Through the end of Spirit's mission, the dynamic brakes on all of the affected actuators were believed to function nominally. However, without reliable state sensing, functioning of the dynamic brakes could not be verified. A failure to open the dynamic brake on an affected actuator would have gone undetected, and motion would have been initiated with the dynamic brake still engaged. Given the fused design of the dynamic brake circuit, proceeding without dynamic brake sensing posed no risk to the rover system. Motion of the actuator against the dynamic brake would either blow the dynamic brake fuse or stall the motion. In the first case, motion would continue uninhibited with no indication of the brake failure. In the second case, the fuse could be manually blown by the ground team, restoring motion of the actuator. Without the dynamic brake, either the magnetic detents would be sufficient to prevent untracked motion of the actuator, or the actuator would gradually lose calibration, which could easily be reestablished.

For the remainder of Spirit's mission, the steering actuators and HGA gimbal actuators showed no indication of dynamic brake failure.

I. Approaching Actuator Life-test Limits

On Sol B-2257 an azimuth actuation on Opportunity's PMA timed out. While the root cause of the error was traced to a failure in the Mini-TES electronics, questions were raised regarding the expected lifetime of the PMA actuators. Over years of operations and several extended missions, the number of cycles on the PMA azimuth actuator was approaching 100 million revolutions.

Considering the possibility that the PMA azimuth actuator could be lost, the operations team considered several options for increasing the probability of a usable failed state. Parking the PMA permanently at an optimal azimuth or limiting azimuth actuation range could ensure the Navcam and Pancam retained visibility, but required turning the rover to point the Pancam and Navcam in azimuth. This option traded PMA azimuth actuation for increased actuation of the steering and drive motors. Returning the PMA to an optimal azimuth after each use would likely increase usage of the PMA azimuth actuator over time, possibly leading to earlier failure. All of these options were considered undesirable.

In absence of any indications of an imminent failure of the PMA azimuth actuator, the operations team began treating azimuth actuator revolutions as a consumable. To extend the probable life of the actuator, several operational adjustments were made to slow the accumulation of motor revolutions. The frequency of Pancam calibration target acquisitions was reduced by requiring that images taken at similar times of sol and within a two sols of each other share calibration imagery. Images of the sun to measure atmospheric opacity were reduced to one acquisition per sol with multiple sun angles imaged on no more than one sol per week. Sky observation frequency was reduced to every third week. Pancam and Navcam mosaics were coordinated to minimize azimuth slewing during and between observations.

IV. Aging Electronics and Software

Thousands of thermal cycles and exposure to the Martian environment have taken a toll on the electrical equipment that forms the brain, nervous system, and energy source for the Spirit and Opportunity rovers. Surprisingly, even rover software has not proven immune to the effects of age. Minuscule computation errors, undetectable or insignificant during the 90 sols of the primary mission, have accumulated to significantly affect operations ten years later. This section describes the degradations and errors seen in electronics and software functionality and the measures taken by the operations team to mitigate their effects.

A. Flash Memory Degradation

After the recovery from the Spirit rover's Sol A-18 flash memory anomaly, the MER flight software was made robust against cases in which the flash memory fails to mount. The flight software runs from one of two easily erasable, programmable, read-only memory (EEPROM) banks and storage on the Rad6000 single board computer. If the flight software is unable to mount the flash file system, a temporary file system is created in the random access memory (RAM). This state is known as "crippled mode".[8]

In crippled mode the rover can function nominally, though all data left in memory will be lost when the RAM is powered off during shutdown. Some Engineering Housekeeping and Analysis (EH&A) data is saved to nonvolatile memory in the EEPROM, but all image files and data products are lost unless downlinked prior to the next shutdown. All boot-related data is lost, so a boot into crippled mode leaves no direct evidence in recorded data. The operations team refers to these missing data periods as "amnesia" events.

On Sol A-1800, Spirit experienced the first amnesia event of the mission. No data was recorded for the awake period between 11:05 LSTA and 12:38 LSTA which included the uplink of the Sol A-1800 sequences and drive plan. A traverse command sequence had been initiated, but drive activities were precluded by command and EH&A reported a mobility error. These facts were symptoms of a standard response by the traverse sequence to a missing setup file. The operations team concluded that the flash memory had failed to mount correctly, and Spirit had booted into crippled mode.

Following this event, the operators developed a sequence to detect crippled mode. This command sequence probed the flash file system, and if it was unreachable, reported a crippled mode event using a data flag saved to EEPROM. Because this flag persists across reboots, a crippled mode boot cycle will be reported at the next communications pass, even when other data have been lost. The crippled mode detector was linked to the software initialization process and autonomously executed at each rover wakeup,

In the months after Sol A-1800, Spirit experienced amnesia events with increasing frequency. The suspected root cause was degradation in the flash memory hardware, causing some sectors to fail health checks, aborting the flash mounting process. To improve Spirit's filesystem reliability, on Sol A-2083 the operations team reformatted the flash memory to exclude the damaged sectors. After reformatting, Spirit's flash errors abated.

Over the past two years, Opportunity has begun showing symptoms of flash degradation. The first amnesia event was seen on Sol B-3082 during a wakeup at 23:18LSTB. Data from the 23:18 to 23:30 LSTB awake period was not saved to flash including the instrument data read out from the APXS. Opportunity experienced similar events on Sols B-3161, B-3177, B-3183, and B-3551. On Sol B-3244 Opportunity EVRs indicated more than one hundred flash block write errors and an autonomous flash power cycle in response. Similar EVRs were seen on Sols B-3286 and B-3336, though on these two sols the inability to write to flash led to a warm reboot of the flight software and termination of ground sequence control. These flash write failures may be related to the amnesia events and may indicate a problem with specific blocks of flash memory.

To track these crippled mode events, Opportunity has been outfitted with the same detector sequence previously used on Spirit. As more events occur, the Opportunity operations team will attempt to identify the location of the damaged flash sectors for exclusion via a flash reformat.

Since it is expected that Opportunity's flash hardware will continue to degrade, several operational measures have been adopted to prevent crippled mode events from causing secondary fault cases. To avoid the loss of data histories from mobility and manipulation activities, command sequences for IDD placements and drives both begin with a filesystem check and abort if flash is non-functional. In addition, APXS instrument data collected overnight is read out just before the next afternoon communications pass, just in case the overnight readout was not saved in flash.

B. Accumulated Error in Rover Attitude Estimation

The rovers maintain and track their position using the Surface Attitude Prediction and Pointing (SAPP) flight software module. SAPP computes a current onboard estimate of rover attitude using integrated IMU data and the position of the sun.[1]

The rover attitude estimated by SAPP is subject to errors from two sources. The first source of error is the position difference between the assumed and actual landing site for each rover. The second source of error is drift in the mission clock, which affects the expected position of the sun.

Errors induced by clock drift vary and tend to accumulate over time. The rate of clock drift is temperature dependent and increases with colder clock temperatures. The temperature of the mission clock is affected by both seasonal conditions and rover activity level. Due to the colder environment Spirit experienced at Gusev Crater, her clock drift attitude error accumulated much more rapidly than Opportunity. When Spirit's mission ended on Sol A-2210, Spirit had accumulated 21 minutes and 48 seconds of mission clock drift. As of Sol B-3570, Opportunity had accumulated 25 minutes and 22 seconds of clock drift. Figure 10 shows the accumulation of East-West attitude error due to clock drift over the course of each rover's mission. Tables 1 and 2 below show the total error in attitude estimation for each rover.

These errors in estimated attitude affect rover operations in various ways. Conversions of science target locations for pointing with PMA azimuth and elevation angles incorporate the error, which is apparent in image panoramas. Due to attitude error, a flat horizon appears sinusoidal, as shown in Figure 11. Attitude errors cause inaccuracy in assessment of the Earth's position relative to the rover deck for HGA communications passes, which may result in poor link margins. Mobility and IDD operations employ a

Table 1. Spirit Attitude Error at End of Mission

Error Source	North-South Error	East-West Error
Landing Site Lat/Lon Error	−0.016°	−0.224°
Clock Drift Error		−5.306°
Total Error	−0.016°	−5.530°
Total Error Magnitude	5.530°	

Table 2. Opportunity Attitude Error on Sol B-3570

Error Source	North-South Error	East-West Error
Landing Site Lat/Lon Error	−0.064°	−0.430°
Clock Drift Error		−5.567°
Total Error	−0.064°	−5.997°
Total Error Magnitude	5.997°	

variety of safety features that monitor the rover's attitude. Because some checks use the SAPP attitude estimate and others use the raw attitude data from the IMU, divergence of attitude values from these sources increases the potential for confusion and error in setting safety check limits. In addition, errors in the SAPP pitch estimate while driving lead to inaccuracies in the estimation of changes in the rover's vertical position.[2]

A technique to reverse the clock drift is currently under development. This technique reduces the error in the spacecraft clock value by a few seconds each sol, responding to concerns that a large instantaneous change in clock value may cause undesirable secondary effects. Initial testing indicates that reversing the clock drift by three seconds per sol is feasible. Once the clock error has been corrected, the operations team plans to limit further error accumulation using frequent corrections of clock drift.

C. Accumulated Error in Estimated Earth Position

Each rover estimates the position of the sun and the Earth in the Martian sky using an onboard vector propagator. The vector propagator uses polynomials to compute the Sun-Earth and Sun-Mars vectors at the current spacecraft time. The polynomial coefficients used in these calculations, optimized for accuracy during the rovers' cruise to Mars and planned 90-Sol primary missions, propagates Earth's position using the Earth geocenter. For long-term accuracy, the Earth-Moon barycenter would have been more appropriate.

Figure 12 shows the error in the Sun-Earth, Sun-Mars, and Mars-Earth vectors as well as the Earth-Mars range. The error in the Mars-Earth vector is greatest when the Earth-Mars range is at a minimum.

Errors in Earth position knowledge combine with SAPP attitude estimation errors, resulting in an overall pointing error for the HGA during direct communications with Earth. Analysis by the operations team has shown that communication into the HGA cannot be supported when the HGA pointing error is greater than nine degrees. During the Earth-Mars closest approach periods in 2005, 2009, and 2010, errors in estimated Earth position remained small enough to cause no operational concerns. In 2012, HGA pointing errors were closely monitored and showed a maximum pointing error of just over six degrees. For the 2014 maximum error period, an HGA pointing error of approximately eight degrees is expected. In the event that pointing dispersion and HGA gimbal position error total more than one degree there is the possibility that uplinks during this period might fail.

The Sun-Earth vector polynomial coefficients are coded into rover flight software and require a flight software update to correct. Without such an update, HGA pointing errors will exceed limits during Earth-Mars closest approach periods in 2016 and beyond, making Opportunity unable to receive commands via the HGA over a period of a month or more during each cycle. If this is the case, the operations team will use other communications paths for the uplink of commands, which may include the Low Gain Antenna or forward-link relay through a Mars-orbiting satellite.

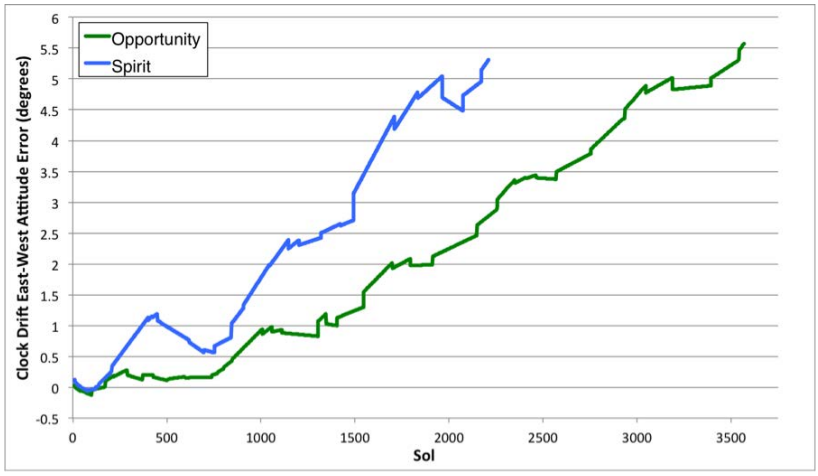


Figure 10. Attitude error due to clock drift.

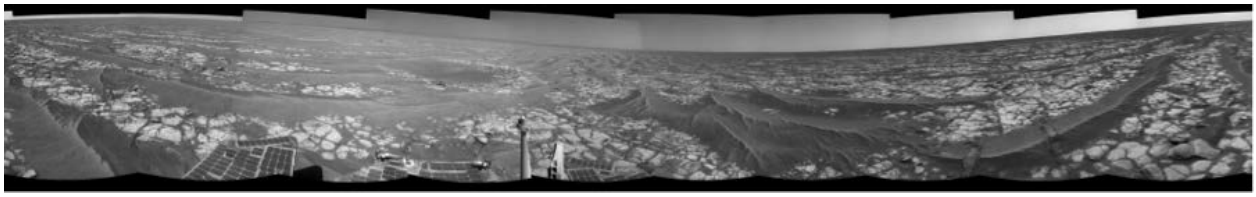


Figure 11. Opportunity panorama from Sol B-2265 showing the effects of attitude errors on image pointing. Image Credit: NASA/JPL-Caltech

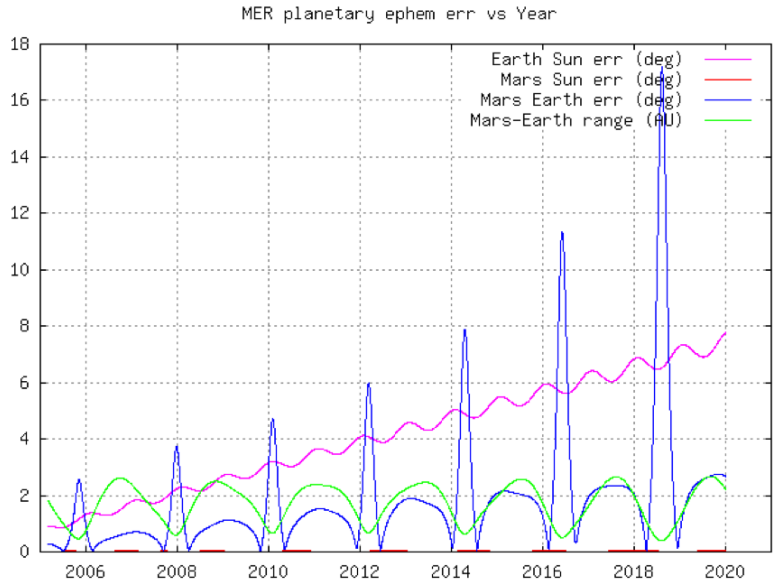


Figure 12. MER Planetary Ephemeris Error vs. Year

D. Loss of Temperature Sensing

Thousands of Martian thermal cycles have lead to the partial or complete failure of many of the platinum resistance thermometers (PRTs) that monitor temperatures of rover components. The loss of PRTs in low thermal inertia locations has limited the team's ability to measure external ambient temperature, resulting in greater uncertainty for model correlation and tactical and strategic planning. Fortunately, two PRTs in low thermal inertia areas (the MI camera and the IDD turret) have only partially failed and still return valid telemetry during certain portions of the Martian day. The IDD turret PRT returns valid telemetry only when the local temperature is above a minimum threshold and the internal windings are brought into contact. This presents a problem during winter operations because it is possible that no valid telemetry is returned if the IDD turret is in an orientation where its temperature never above the threshold. The MI camera PRT behaves differently due to its internal mounting location, displaying valid telemetry only during portions of the Martian day when atmospheric temperature ramp rates are low. To compensate for the loss of external temperature monitoring, the thermal model is correlated to the available MI camera and IDD turret telemetry, providing an estimated profile of external ambient and component temperatures.

PRT readings are used onboard the rovers to select temperature-dependent current limits and control parameters for some actuators, including the joints of the IDD. Initially, the IDD turret PRT was the primary sensor for determining thermal set points for the IDD elbow, wrist, and turret joints. When the partial failure of the IDD turret PRT made its state unreliable, the team began using the MI camera PRT instead. Now that the MI camera PRT has also partially failed, the team is using the PRT on the MI electronics to determine the operating temperature of the IDD joints.

E. Aging Power System

The solar power source used for both Spirit and Opportunity was a driving factor in limiting their primary mission durations to 90 Martian sols. It was expected that dust accumulation on the solar panels would reduce solar power generation by 20% after 90 sols on the Martian surface. The development team predicted that these power losses would result in insufficient power for battery, flight computer, and Mini-TES survival heating by winter. After the rovers' arrival on the Martian surface, more power was available for activities than the worst-case estimates had suggested. In addition, performance data collected during the primary mission reduced uncertainty in modeled power predictions, reducing tactical power margins and increasing the power available for surface activities. These factors, along with limited use of the survival heaters, enabled the rovers to operate through not just one, but several Martian winters.

Over ten years of operations, the power production and storage systems have experienced some degradations in performance. In general these degradations limit rover activities, particularly overnight. Power limitations also necessitate the implementation of strict operational restrictions during the winter months. The most notable contributors to degradation of the power system are reduction in the capacity of the onboard battery packs and accumulation of dust on the solar arrays.

1. Reduced Battery Capacity

The Spirit and Opportunity rovers each carry two 8-cell Lithium-ion secondary batteries for a total capacity of 22 Amp-hours. MER is the second planetary mission to use Li-ion batteries, but the first to use them during operations on the Martian surface. The Li-ion batteries have proven to be reliable and robust and are now the standard technology for Mars surface missions.

With time and usage the loss of battery capacity is unavoidable. The batteries degrade more rapidly at high temperature and high voltage. Deep discharges of 70% depth of discharge or more also reduce battery capacity. To maintain the rovers' battery capacity, the operations team attempts to operate the batteries between 25% and 50% depth of discharge as illustrated in Figure 13. This careful use of the batteries has resulted in only 15% overall capacity fade over the first decade of the surface mission. When Spirit's mission ended, her battery capacity was estimated at 16.9 Amp-hours. At the time of this writing, Opportunity's battery capacity is estimated at 17.5 Amp-hours.

Reduced battery capacity limits rover activities, particularly in the late afternoon and overnight, when the solar panels are producing no power. Opportunity's reduced battery capacity, coupled with the large overnight energy expenditure of the stuck IDD heater, has practically eliminated the rover's capability to support overnight relay communications.

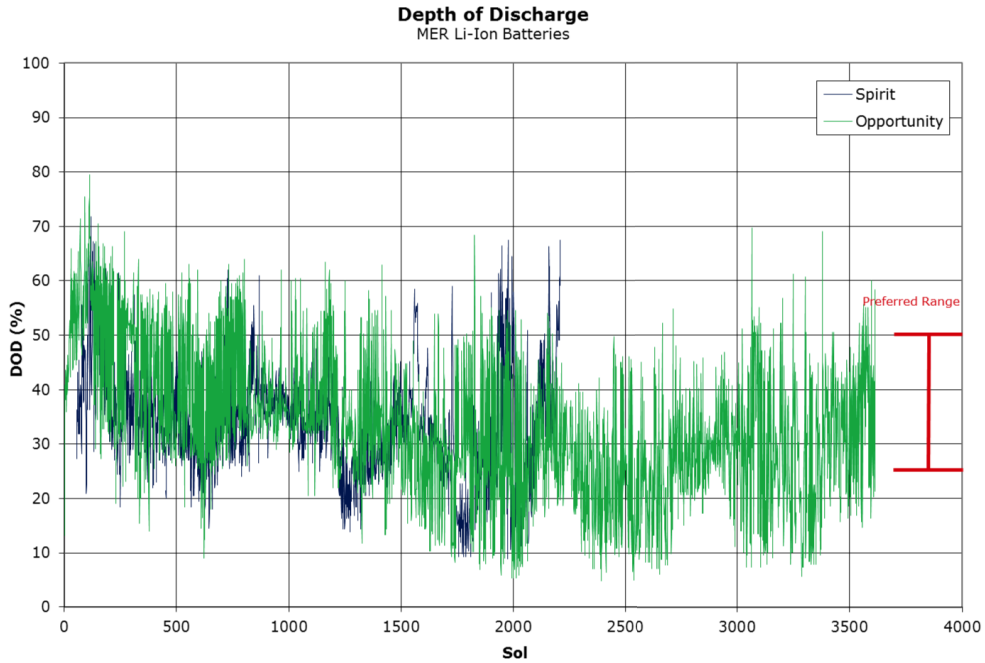


Figure 13. Battery discharge history for Spirit and Opportunity rovers.

2. Latent Dust Obscuring the Solar Array

Based on Mars Pathfinder data, the operations team expected that enough dust would accumulate on the rover's solar arrays during the 90-sol primary mission to block 20% of the sunlight reaching the panels. Actual dust accumulation showed this prediction was accurate. Dust continued to accumulate on Spirit until Sol A-420, when most of the dust was cleaned off the array, presumably by Martian wind effects. Opportunity also benefited from numerous dust cleaning events over the course of the mission, but they were smaller and more numerous than those seen on Spirit. These dust cleaning events enabled the rovers to produce sufficient energy to operate for much longer than originally anticipated.

Dusty arrays lead to severe power limitations for Spirit and Opportunity during dust storms, which obscure the sun, and during the Martian winter, when the sun's zenith is low in the sky. To survive, the operations team devised methods for both reducing rover power requirements and increasing solar energy production. One method used to conserve energy was prevention of unnecessary heating. Keeping the rover active caused the flight computer and other electronics to warm the insulated electronics box, resulting in internal temperatures high enough to make overnight heating unnecessary. For both rovers, the Mini-TES survival heaters were turned off, risking the instrument's health, but saving as much as 60 Watt-hours each sol.

During winter, low sun angles resulted in poor energy production by the solar arrays. To increase power generation, the team operated the rovers on sloped terrain that tilted the solar array toward the north, improving the relative angle between the panels and the sun. To survive the winter, the Opportunity rover has required northward tilts of approximately 15°, while Spirit, located further south, required northward tilts of up to 27°.

V. Aging Mission

The unexpectedly long duration of the Mars Exploration Rovers' mission has also caused complications from a programmatic perspective. The continued operation of Spirit and Opportunity required the allocation of ground resources and personnel expected to become available for other uses. As years passed, the rovers experienced growing competition for communications resources, operations team members, and office space. This section presents these challenges.

A. Competition for Communications Resources

Communicating with Spirit and Opportunity requires the coordination of several assets on Earth and at Mars. Communicating with Earth directly requires access to one of the ground stations in the Deep Space Network (DSN), which are shared among dozens of interplanetary spacecraft. Relaying data to or from the rovers through Mars orbiting satellites requires coordination with those assets' science teams as well as DSN coverage for returning orbiter-stored data to Earth.

Early in the rovers' surface mission, Spirit and Opportunity had high priority for access to communications assets. Spirit and Opportunity had plenty of access to DSN ground stations and multiple relay overflights per sol from both Mars Odyssey (ODY) and Mars Global Surveyor (MGS). Each team developed a steady communications pattern of uplinking command files directly from Earth each Martian morning and receiving downlink from one or more satellite relay passes each afternoon to enable planning of the next sol's activities. When power permitted, additional overnight relay passes might return additional data.

However, as the prime mission passed into several extended missions, coordinating assets for telecommunications became increasingly difficult. The loss of MGS in 2006 reduced the availability of relay passes. Although the Mars Reconnaissance Orbiter (MRO) had arrived at Mars and began offering relay passes to Spirit and Opportunity, MRO relay technology was minimally compatible with the older rovers, and data return was unpredictable. As future missions to the Martian surface were planned, extending the lifetime of the ODY relay transmitter became a priority. To reduce ODY transmitter usage, handshaking between relay and rover was eliminated for overnight relay passes. This increased the incidence of lost or corrupted downlink for overnight passes, but enabled ODY to receive rover data without powering her transmitter, reducing transmitter wear by 50%.

The presence of MRO in Mars orbit brought major complications for Spirit rover operators. Developers of MRO, never imagining that Spirit would survive her first Martian winter, outfitted the orbiter with a duplicate of the rover's radio. Spirit and MRO had identical addresses for radio communications. Radio signals meant for one could be received and interpreted by both. For the remainder of Spirit's mission, every communication to the rover required coordination with the MRO operations team to ensure that MRO wasn't listening in on commands transmitted to Spirit.

The arrival of new Martian surface missions, first the Mars Phoenix Lander in 2008 and later the Mars Science Laboratory Curiosity rover in 2012, necessitated sharing of the limited ODY buffer for relayed data. The ODY relay buffer barely accommodated the twin rovers, and Spirit and Opportunity teams often had to coordinate communications to avoid overwriting each other's data. When Phoenix operated on Mars from May through November of 2008, the buffer was partitioned to give each mission a smaller, dedicated buffer, temporarily restricting use of the relay by Spirit and Opportunity. In 2012, the ODY buffer was again partitioned to accommodate the needs of the Curiosity rover.

The growing number of spacecraft also affected the rovers' access to DSN ground stations. Here Sprit and Opportunity compete with other Mars landed assets, Mars orbiters, and any other spacecraft in that part of the sky. The experience gained through years of operation has refined MER DSN requests to about an hour and a half per planning day. Further, since these requests are usually for data uplink only, other missions can use the station for downlink during that time. Nevertheless, with the reduced priority of an older mission, Opportunity cannot always reserve the most optimal DSN time for uplinks, and sometimes a late uplink significantly reduces the time available for critical rover activities on the affected sol.

In today's active Martian exploration community, communications planning is a constant series of negotiations over limited resources.

B. Team Evolution and Transfer of Expertise

During MER's prime mission, the operations team numbered in the hundreds, staffing operations shifts for two rovers, twenty-four hours each day and seven days each week. Many of these operators came from the MER development team and had very detailed technical knowledge of the rovers' design and engineering characteristics. These rover experts, planning for 90 sols of operations, had arranged to transition to new projects as the prime mission drew to a close. This presented the project with three challenges.

The first challenge was transitioning from overnight operations to a pace more sustainable for the long term. Refinement of key roles, reduction of plan complexity, libraries of reusable instrument sequences, and increased automation of the sequencing process enabled command uploads to be prepared and validated within an 8-hour workday.[7]

The second challenge facing extended operations was a dwindling workforce. Despite an influx of new, enthusiastic personnel, the demand of new projects under development along with reduced funding levels for the extended mission dictated a smaller overall team. Increasingly routine activity plans enabled further automation of ground tools, which in turn enabled a single team member to perform multiple roles within a single planning cycle. During the prime mission, Tactical Activity Planner, Sequence Integration Engineer 1, and Sequence Integration Engineer 2 were three separate roles; today one operator performs all three functions in a single workday. As the team became smaller, the incentive to cross-train individuals in other roles increased. Cross-training created operators with a breadth of knowledge and experience spanning several areas of expertise, individuals with unique abilities to identify process improvements in cross-role interactions, further streamlining operations.

The third challenge was that many of the people leaving the project took special and unique knowledge with them. In the early days, many of the operators had also been developers. They had built, tested, or assembled the rovers, generating detailed and in many cases singular knowledge about rover functionality. Some knowledge retention was achieved by embedding experience and "lessons learned" into the automated ground tools. For example, the rover planner "flight rule check" script scans mobility and manipulation sequences for compliance with over 130 rules capturing the collective operational experience of ten years on Mars. Expertise is also captured in accumulated libraries of reference materials continuously updated by the current team of experts. The development of thorough training processes ensures that incoming operators are exposed to all the lessons their predecessors have learned, in addition to the nominal operations routine. Equally important is an atmosphere of rigorous verification, in which temporizing is discouraged and frequent referral to vetted references is the standard.

Throughout the mission, maintaining open lines of communication between engineers and scientists, sequencing team and engineering team, and past and present operators has proven essential. As rover systems degrade and fail, causing new anomalies and requiring ever more innovative workarounds, the operations team continues to consult the experts who designed, built, and tested Spirit and Opportunity.

VI. Conclusion

In 2004, Spirit and Opportunity were in their prime missions and at close to optimal functionality. The rovers survived to explore for years longer than expected but suffered myriad failures and degradations. Some science instruments, thermistors, and actuators failed and their functionality was lost. Camera images, position knowledge, battery capacity, and pointing accuracy have degraded. These failures affect vision, communication, mobility, and dexterity. Competition for resources and personnel have slowed the turnaround times for anomaly response and cause the rover to progress more slowly, particularly on long surface campaigns.

Through all of these challenges, the dedicated and innovative work of the operations team enabled the rovers to continue their productive and inspirational mission of exploration. Ten years after two successful prime missions drew to a close, the Mars Exploration Rovers mission continues to visit unseen places on the Martian surface and return compelling scientific discoveries.

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