

Mars Exploration Rover Surface Operations: Driving Opportunity at Meridiani Planum

Eric T. Baumgartner, Jeffrey J. Biesiadecki, Robert G. Bonitz, Brian K. Cooper, Frank R. Hartman,
P. Christopher Leger, Mark W. Maimone, Scott A. Maxwell, Ashitey Trebi-Ollenu, John R. Wright

Jet Propulsion Laboratory
Pasadena, CA USA
Jeffrey.J.Biesiadecki@jpl.nasa.gov

Abstract— On January 24, 2004, the Mars Exploration Rover named *Opportunity* successfully landed in the region of Mars known as Meridiani Planum, a vast plain dotted with craters where orbiting spacecraft had detected the signatures of minerals believed to have formed in liquid water.

The first pictures back from *Opportunity* revealed that the rover had landed in a crater roughly 20 meters in diameter – the only sizeable crater within hundreds of meters – which became known as Eagle Crater. And in the walls of this crater just meters away was the bedrock MER scientists had been hoping to find, which would ultimately prove that this region of Mars did indeed have a watery past.

Opportunity explored Eagle Crater for almost two months, then drove more than 700 meters in one month to its next destination, the much larger Endurance Crater. After surveying the outside of Endurance Crater, *Opportunity* drove into the crater and meticulously studied it for six months. Then it went to examine the heat shield that had protected *Opportunity* during its descent through the Martian atmosphere.

More than a year since landing, *Opportunity* is still going strong and is currently en route to Victoria Crater – more than six kilometers from Endurance Crater. *Opportunity* drove more than four kilometers in all as of sol 410, examined more than eighty patches of rock and soil with instruments on the robotic arm, excavated four trenches for subsurface sampling, and sent back well over thirty thousand images of Mars – ranging from grand panoramas to up close microscopic views.

This paper will detail the experience of driving *Opportunity* through this alien landscape from the point of view of the Rover Planners, the people who tell the rover where to drive and how to use its robotic arm.

I. INTRODUCTION

Opportunity is the second of two identical rovers sent to Mars under the Mars Exploration Rover (MER) project, and landed in the region of Mars known as Meridiani Planum in January 2004. The first rover *Spirit* [1] landed three weeks earlier on the opposite side of the planet in Gusev Crater. The primary mission for both rovers is to search for evidence of past water on Mars.

To enable a study of rocks and soil at many diverse targets, the rovers were required to be able to survive 90 Martian days (called “sols”), drive safely as far as 100 meters in a single sol in Viking Lander 1 (VL1) terrain, and achieve a total distance of at least 600 meters over the 90 sol mission. Furthermore, the rovers were required to approach rock and soil targets of interest as far as 2 meters away in a single sol, with sufficient accuracy to enable immediate science instrument placement on the next sol without further repositioning.

To meet these objectives, the rovers were outfitted with a robotic arm (the *Instrument Deployment Device*, or IDD) for placing the science instruments on rocks and soil [2], a six wheeled rocker-bogie mobility system, and several pairs of stereo cameras for engineering use.

The mobility system has six 25 centimeter diameter wheels, of which the four corner wheels may be steered – a mechanical configuration derived from the Mars Pathfinder rover Sojourner [7]. The rover body has 30 centimeter ground clearance, and large solar panels on the top of the rover require additional clearance to tall rocks (60 centimeters from ground to solar panel). Wheel baseline is roughly 1 meter side-to-side and 1.25 meters front-to-back. The MER rovers can turn-in-place about a point between the two middle wheels, drive straight forward or backward, and have at best a one meter turn radius for driving along circular arcs. Straight line driving speed is set to 3.75 centimeters/second (roughly 75% of the maximum motor speed), and the rover turns in place at roughly 2.1 degrees/second. The rovers are statically stable at tilts of more than 40 degrees, however, driving on more than 30 degree slopes is not recommended due to the possibility of uncontrolled sliding. Rocks larger than a wheel are considered mobility hazards.

The flight computer selected was the RAD6K, also used on Mars Pathfinder lander, a 20 MHz radiation-hard computer that can function at cold temperatures and with low power. While reliable and fast enough to meet mission requirements,

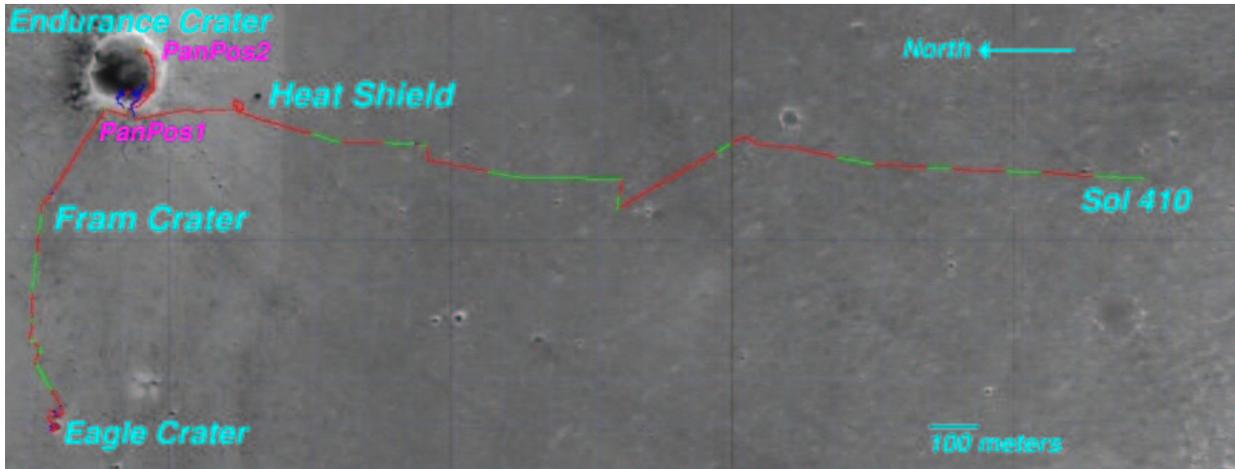


Fig. 1. Plot of *Opportunity*'s rover-reported position through Sol 410. Red indicates blind driving, green auto hazard avoidance, and blue visodom.

it is none-the-less a slow computer and machine vision processing and image compression take a long time.

The MER rovers are typically commanded once per Martian day, so they need to have substantial autonomy to meet their requirements. A sequence of commands sent in the morning specifies the day's activities: what images and data to collect, how to position the robotic arm, and where to drive. Then at the end of each day, the rovers send back the images and data human operators will use to plan the next day's activities. The next day's mobility commands are selected by the Rover Planners (RPs) based on what is known – and what is unknown – about the terrain ahead.

The rovers are driven using three primary modes: low-level commands that specify exactly how much to turn each wheel and position steering actuators, directed driving primitives for driving along circular arcs (of which straight line driving and turn-in-place are special cases), and autonomous path selection. Low-level commands enable "non-standard" activities such as using the wheels to dig holes in Martian soil, scuff rocks, and perform mechanism health diagnostic tests. Directed drives allow human operators to specify exactly which driving primitives (ARC, TURN_ABSOLUTE, TURN_RELATIVE, TURN_TO) the rover will perform. Autonomous path selection mode (GO_TO_WAYPOINT) allows the rover to select which driving primitives to execute in order to reach a goal location supplied by human operators.

Both directed and path selection modes of driving can make use of on-board Stereo Vision processing and Terrain Analysis software [5], [6] to determine whether the rover would encounter any geometric hazards as it drives along its chosen path. In directed driving, the rover can preemptively "veto" a specific mobility command from the ground if it appears too risky. In Autonomous Navigation (autonav)

and other path selection modes, the rover can select its own driving primitives to steer around obstacles and make progress toward its goal. This software provided the unique capability of enabling the vehicle to drive safely even through areas never before seen on Earth: more than 1100 meters of the 4260 meters driven on *Opportunity* as of sol 410 were driven using autonomous hazard avoidance.

The rovers maintain an estimate of their local position and orientation updated at 8 Hz while driving. Position is first estimated based on how much the wheels have turned (wheel odometry). Orientation is estimated using an Inertial Measurement Unit that has 3-axis accelerometers and 3-axis angular rate sensors [4]. In between driving primitives, the rover can make use of camera-based Visual Odometry (visodom) to correct the errors in the initial wheel odometry-based estimate that occur when the wheels lose traction on large rocks and steep slopes. Visodom software [3] has generated over 800 successful position updates on *Opportunity*.

Typical traverse rates are: 120 meters/hour blind driving, 30 meters/hour hazard avoidance in benign terrain, and roughly 10 meters/hour visodom (without hazard avoidance).

Mobility sequences are *event-driven*: the next command executes only after the previous one completes. Sequences can have *conditionally* executed commands, where variables in the sequence are checked at run-time by "IF" statements. The most important variables are those that measure straight-line distance from current rover position to a sequence-defined target position, and the mobility fault type which indicates what type (if any) of mobility error has occurred. Use of conditionals allows Rover Planners to write more flexible sequences that can not only detect dynamic deviations from the planned drive, but can also compensate for them and therefore achieve longer drive distances.

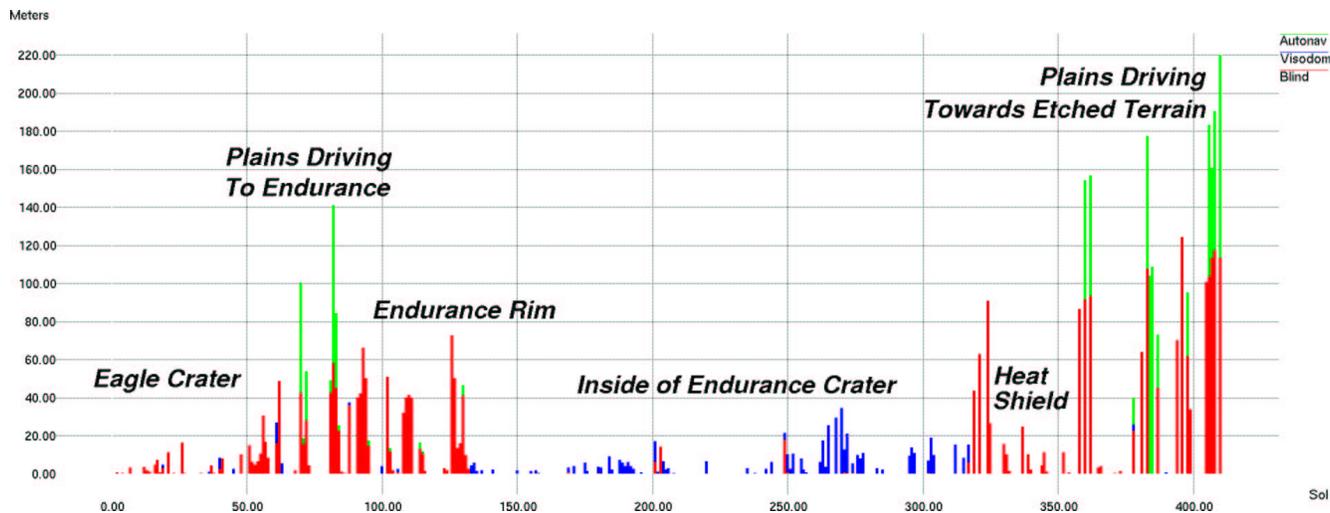


Fig. 2. *Opportunity* odometry for Sols 1 through 410. Red indicates blind driving, green autonomous hazard avoidance, and blue visual odometry.

II. SOLS 1–60: EAGLE CRATER

The first images sent by *Opportunity* after landing revealed its landing site to be inside a small crater, which would be called Eagle Crater. Excitingly, an outcrop of bedrock could be seen on the crater walls just a few meters from the lander. The crater itself was roughly 20 meters across and 2 meters deep. The bottom of the crater was filled with loose, fine sand, and the northwest wall had the exposed bedrock. Although at the time the bedrock looked imposing and slopes of 15 or more degrees seemed excessive, really there were no mobility hazards in the crater **OTHER THAN THE LANDER ITSELF**, to which we always had to give wide berth.

The first seven sols were spent readying the rover for its primary mission. It had to deploy its mast, deploy its mobility system which was carefully folded up to fit in the tight confines of the Mars Pathfinder-sized lander shell (“standup deployments”), and take “mission success” PANCAM and MTES panoramas prior to driving off of the lander.

After the rover stood up, we got a better view of the surrounding landscape – and found it flat and featureless. So featureless, it was difficult to do machine stereo correlation on images taken with the left and right eyes of our cameras. This was a particular problem with the 120 degree field of view HAZCAMs. Using larger sized images and decreasing the amount of compression made automated analysis of the IDD work volume possible, but we would have to come up with a different approach for autonav once we eventually left the crater.

During these first sols, it was determined that a heater used to warm IDD actuators for use in the cold Martian

environment was stuck “on”. Attempts to turn this heater off failed. Fortunately, a separate thermostat would eventually cut power to the heater when sufficiently warm, but this was still not under operator control. Typically the heater would turn on and start drawing power at 7:30 p.m. Mars time, and not turn off again until roughly 8:00 a.m., drawing substantial power all night.

This set constraints that affected when and what types of activities could be performed. IDD activities would not be allowed to start until the actuators had cooled down (!) to nominal operating temperatures – 11:30 a.m. Mars time.

The first order of business after egress was an immediate series of IDD observations of the soil next to the lander. Then on sol 12, we performed checkout of basic mobility commands during a short drive towards the outcrop. Sol 13 had us driving to our first target on the wall of the crater. For this and the next forty sols, we had to pay close attention to the slopes on the crater walls. The rover’s primary means of estimating its position is based on counting how many times it turns its wheels. This method works well when the wheels have good traction, but the rover slid considerably on the sloped crater walls.

Because we landed in such a scientifically interesting site, almost every sol we were in Eagle crater saw IDD usage. But this impacted mobility, because the rover cannot drive until the IDD is put in its stowed configuration - safely tucked above the ground to protect it from rocks. Thus we could not start driving until after stowing the IDD at 11:30 a.m., hours later than *Spirit* was able to operate. Combined with the excessive power draw from the IDD heater at night, there was typically very little time and power for driving.

Minimizing drive time meant that most drives had to

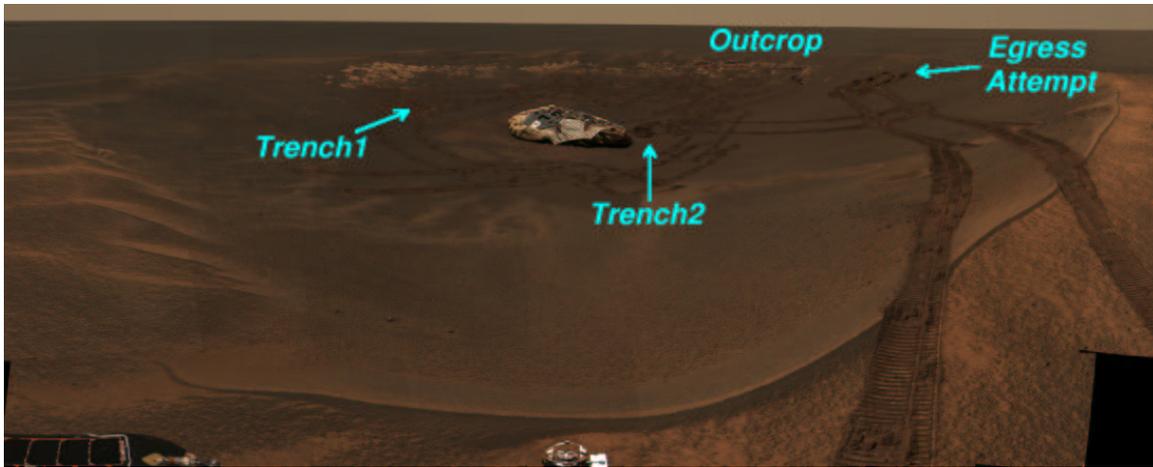


Fig. 3. Eagle Crater roughly 20 meters in diameter, as seen on sols 58 and 60 – “Lion King” panorama.

be done in “blind” mode, without benefits of the visual odometry capability and autonomous navigation. The time required to process images on-board for these techniques was generally too prohibitive during the initial sols.

With considerable slip and time constraints preventing use of visodom, we knew the rover’s internal position estimate would not be very accurate. Not making use of the internal position estimate precluded the use of GO_TO_WAYPOINT and TURN_TO commands, conditional sequencing based on estimated distance to a Cartesian location, and even remote sensing commands designed to image specific X,Y,Z coordinates. Instead, our mobility sequences were almost all geared to using combinations of TURN_ABSOLUTE and ARC commands based on predictions of what our slip would likely be. Similarly, RPs worked closely with those designing imaging sequences, to point cameras at specific azimuths/elevations instead of 3D coordinates.

The targets of interest lined the crater wall. The IDD is mounted on the front of the rover, so we generally ended drives with the rover pointing uphill. The next science targets of interest were invariably lateral on the crater wall. If the rover had six wheel steering, repositioning would have been a snap – many drives could have simply been sideways.

However, due to mass and volume constraints, the MER rovers do not have the ability to steer their center wheels, meaning they cannot drive sideways. Repositioning to subsequent targets was done with “V”-shaped and “U”-shaped maneuvers. The “V” maneuver started with a backwards drive downhill to where the slopes flattened out a bit, a turn-in-place to point the front of the rover at the next target of interest, and a forward drive towards the target. The downhill drives were *undercommanded* to account for slip, and the uphill drives were similarly *overcommanded*.

In general, when targets required cross slope drives of more than a couple meters, we modified the “V” maneuver to instead be “U” shaped: two mostly straight uphill/downhill bumps with a longer cross-slope drive at the lower elevations in the crater where slip would not be as extreme.

Motivating the “U” and “V” shaped drives was the fact that slip was reasonably predictable when the rover was pointed predominantly uphill, and only the commanded arc length needed adjusting to account for longitudinal slip. For cross-slope driving, small amounts of transverse slip were accounted for by pointing the rover uphill of its intended target. Not surprisingly, the amount of slip was dramatically less when we had wheels on outcrop rock itself, as opposed to pure loose sand. Predicting the amount of slip really was a black art, combining results of testing on a sand-covered tilt platform on Earth, the number of wheels expected to be driving on rock, terrain slope, and actual slip seen on any recent drives over similar terrain. We always strove to nail our approaches, but slip prediction took on a whole new level of importance for drives near the lander - which would cause serious problems if we raked a solar panel along it or got caught up in the flexible ramps that had helped us egress.

After spending enough time agonizing over predicting slip, we were given time to checkout the onboard visual odometry capability. On Sol 19, we performed an initial flight checkout test where the computations would be made on board, but not applied to the position estimate itself. That test passed, so we used visual odometry again on sols 36, 40 and 45, where we paused mid-drive to take some images of a target specified in X,Y,Z Cartesian coordinates – and the pointing was perfect. Visodom had accurately tracked the rover’s true position despite the slip encountered.

After almost two months in a relatively small crater, it

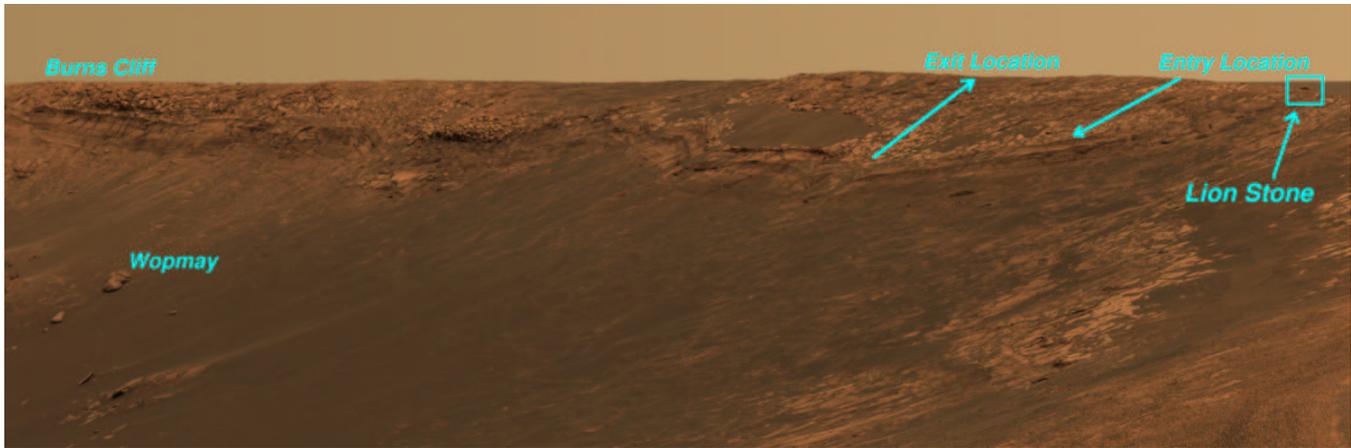


Fig. 4. Endurance Crater roughly 150 meters in diameter, Burns Cliff to Lion Stone, as seen on sols 97 and 98 at Panorama Position 1

was starting to seem a bit too much like home. Rover lifetime was still unknown, and the plains outside of the crater looked completely barren. The next nearby large crater was Endurance, but that was more than 700 meters away – further than the required mission success distance. After debate amongst the scientists, we finally decided to wrap up exploration of Eagle Crater, and move on towards Endurance.

The last observations were soils, and were where we saw the highest slips. We dug a trench on the crater floor, where the tilts were less than 5 degrees, yet we still slid 25 centimeters during the digging – troubling because of our proximity to the lander. Following the trenching, we drove to a staging point for the upcoming crater egress, and saw considerable slip even on slopes of less than 15 degrees. And on the following day, the rover got bogged down and actually hit 100% slip during one 12.5 meter segment to drive straight uphill and out of the crater. That egress sequence finished with a cross-slope drive that was intended to be performed outside the crater. It wound up being roughly 45 degrees off of straight uphill, during which the rover did not experience dramatic slip. The next day, sol 57, we continued the drive in the same direction with liberal overcommanding - and we were out of Eagle Crater!

Our experience at Eagle Crater was just a warmup for Endurance, where again we would spend months driving on high slopes, constantly referring to images taken many sols previously, and getting intimately familiar with the surroundings to the point where again it felt like home.

III. SOLS 61–94: PLAINS TO ENDURANCE CRATER

Just east of the crater was a rock we had seen early on, out on the plains all by itself. Amazingly enough, we happened to bounce right on this lone rock during landing – hence the rock was named “Bounce Rock”. During the drive to Bounce

Rock, we did experiment with visual odometry, and found that the plains just did not have enough visual features to track, and visodom did not always provide position updates.

The featureless terrain not only caused problems for visodom (which at least we would not actually need here since the terrain was so flat), but also for the hazard avoidance cameras. After having spent two months doing constant IDD work and short drives and target approaches, the *Opportunity* RPs were ready to fly across the plains as the *Spirit* RPs had been doing for some time. As on *Spirit*, the plains drives all started with a long blind drive. We also wanted to then kick into hazard avoidance mode, but the HAZCAMs would not correlate consistently on this terrain.

After studying images from Eagle Crater we realized that NAVCAMs could be used effectively for autonav driving, and updated the onboard flight software to better integrate NAVCAMs into autonav processing. Additionally, to mitigate the stuck IDD heater, the update also added the ability to “deep sleep”, which meant taking the batteries off of the power bus at night. The rover would then wake up only when the sun got bright enough in the morning - it would not be able to wake up on a timer when doing deep sleep.

The plains turned out to have interesting geological features. We came across several large fissures, the largest one called Anatolia. And a small crater perhaps 9 meters across, which we called Fram Crater, with fresh ejecta nearby. It was questionable as to whether or not the rover would get stuck in these fissures and small craters – the first egress attempt at Eagle Crater was a reminder to be cautious. So we assiduously avoided driving through larger ditches.

We tracked our progress by finding those features visible from the rover in maps made from orbital imagery, but overall, navigating to Endurance was not difficult because

we could see the rim of Endurance from far away. As the rim of the crater loomed larger each day, and as we began to make out what looked like cliffs on the southeast rim, the excitement steadily built up. Between Bounce Rock, the Anatolia fissures, trenching, Fram Crater, and several drives of more than 100 meters each, the sols passed quickly and we arrived at the rim of Endurance Crater on sol 95.

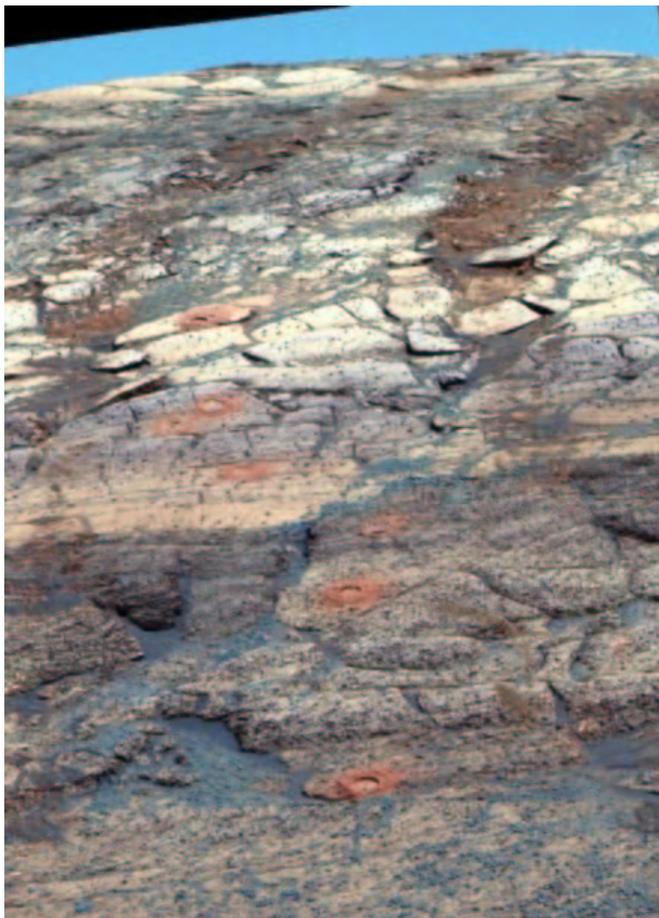


Fig. 5. False color image taken on sol 173 showing RAT holes and rover tracks made during descent into Endurance Crater.

IV. SOLS 95–131: ON THE RIM OF ENDURANCE CRATER

Our first peek inside Endurance showed magnificent rocky outcrops along the rim, beautiful sand ripples and tendrils on the crater floor, treacherous cliffs and drop-offs, and a couple of large boulders. Orbital imagery showed the crater to be about 150 meters in diameter; we now also saw that it was more than 20 meters deep.

And it appeared there were places the rover could safely enter the crater without tipping over. However, slopes would be higher than either rover had been on, and ground testing

and our first egress attempt at Eagle crater suggested that getting back out again might be difficult. But examining the outcrops up close was extremely important scientifically; they would reveal a much longer view of Mars history than what we saw at Eagle crater.

We decided that before entering, we would survey the interior from multiple locations along the rim. This would give us good views into portions of the crater we may not be able to drive close to even from inside, and let us assess more potential ingress locations for safety and likelihood of subsequent egress. And, it would allow more time for additional testing here on Earth, to see how our test rovers climbed on steeper but rockier surfaces.

Our first stop was a rock perched on the outer rim of the crater approximately 50 meters southeast (we drove counter-clockwise around the crater at first), which we called Lion Stone. This rock proved very useful for localization.

Drives along the rim were all done with ARC and TURN_ABSOLUTE commands. We were driving on generally rocky berm, on a slope that was away from the crater interior (so slip would take us away from the rim itself, which we liked). The drives were kept short enough that we had a clear view of our drive path and could verify it was clear of obstacles and ejecta. We avoided doing sharp “dog legs”, because we were driving far enough that stereo range data was not precise and we did not trust the precision of our localization in the orbital maps. So most days were straight drive segments, approximately 40 meters per sol.

We continued about one third around the crater rim, for another approach and a second panorama. We could see from imaging done at our first approach location and at Lion Stone that the crater wall at this location was dangerously steep. The approach was split into multiple sols, with sol 116 being only a 1.5 meter bump right to the edge.

From our various vantage points, it appeared that about 6 meters east of Lion Stone was our best entry location. It was rocky, which would be good for traction, relatively smooth, and had an overall slope of roughly 25 degrees. Ground testing performed by R. Lindemann had shown our test rover could climb rocky slopes of at least 30 degrees. And the long rocky slope would still allow science measurements of the outcrop to be made at various depths, without requiring long traverses inside the crater, should we decide it was not safe to proceed further.

While we had originally considered continuing around Endurance counter-clockwise for a third evenly-spaced panorama from the rim, it was decided the time needed for this amount of driving was not worth it, and since we had found a good entry location, we backtracked towards Lion Stone and reached our intended ingress location in 5 sols of driving, having driven a total of roughly 200 meters.

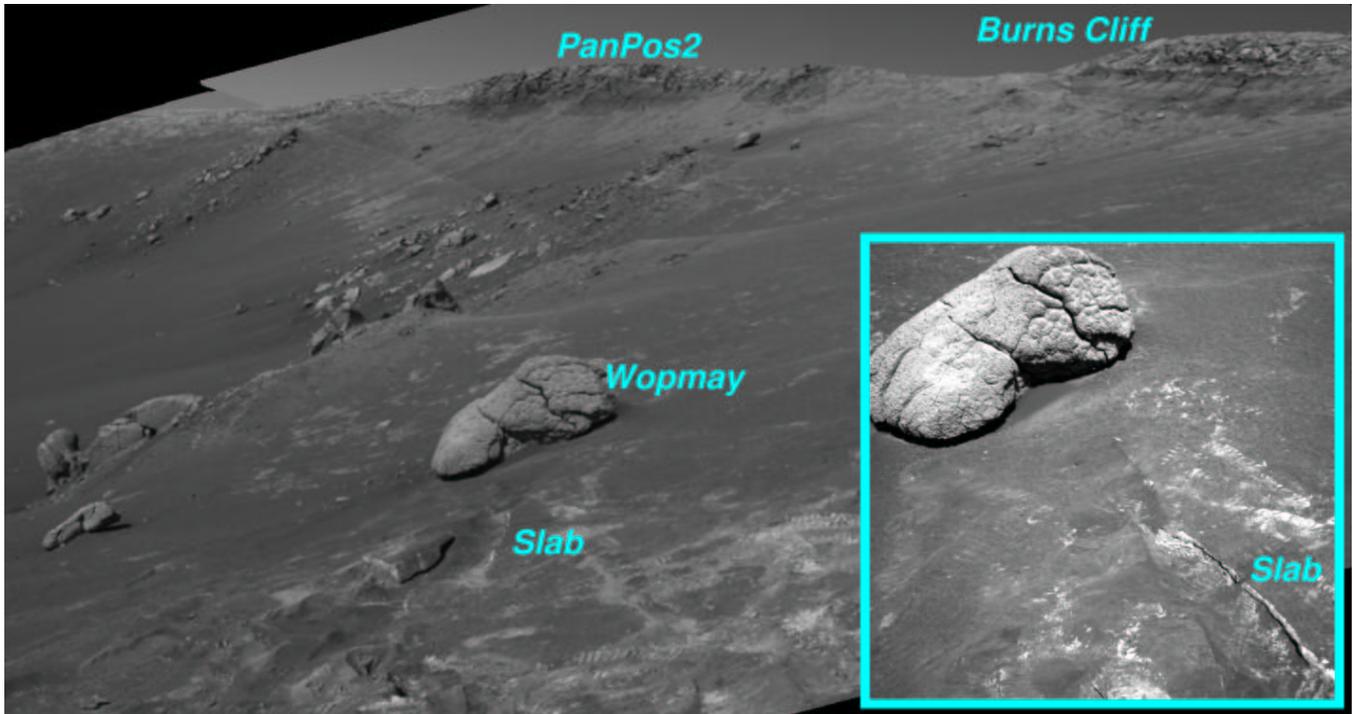


Fig. 6. Wopmay and rover tracks showing very soft surrounding terrain, taken sol 268, inset shows freshly exposed slab taken sol 264

V. SOLS 132–315: INSIDE ENDURANCE CRATER

After the careful survey of ingress locations, crater entry itself was also done very cautiously. The Mechanical team had done much testing on a large tilt platform and indicated that, on rock, the rover would climb best straight uphill. Also, it climbed slightly better backwards, bogies uphill. Since the mast is at the front of the rover, we would go in forward and straight downslope. On sol 132, we drove so just the front wheels were inside, and the next sol was a “toe dip” in which we drove so that all six wheels were in and then backed fully out, to verify our ability to leave before continuing further. This test was successful – we saw very little slip going in or out due to the good traction on rock.

So we went back in and began a careful survey of the outcrop with the IDD. Drives were short, less than 2 meters per sol with IDD observations in between and periodic backups to prove we could still climb. We carefully predicted terrain slope ahead of the rover, and kept the rover’s fault protection limit for excessive tilt set to a hair trigger – generally just 1 degree above predict. If our predicts were incorrect, we wanted the rover to stop quickly so we could reassess, but this never happened.

The most exciting part of our descent was on sol 157, when our drive ended with a small turn-in-place to keep us pointed downhill on the 26 degree slope. When doing

ARC’s and turns, the rover runs all four steering actuators simultaneously – and during this turn, the front wheels briefly lost traction and slipped downhill a few centimeters. The middle wheels held traction, causing the rear wheels to lift off the ground and the rover body to tilt forward slightly. While this “wheelie’ing” was not an unexpected occurrence, it did confirm we were operating at tilts where traction was getting less certain, and slip could be erratic. The next sol we got all six wheels back on the ground by running the middle wheels alone in the forward direction. Slip induced while steering would be minimized by staggering the actuation so only one or two of the actuators would move at a time.

In contrast to Eagle crater, our drives were short enough and our slopes steep enough that we used visual odometry almost every step of the way. This greatly simplified localization and slip assessment, which had to be done quickly. In addition to keeping the step sizes small enough so that we would have at least 60% overlap from one visodom image to the next (roughly 50 to 60 centimeter steps), it was important to point the cameras at terrain as feature-rich as possible, and as perpendicular to the direction of travel as possible. This minimized scale changes in features tracked from one image to the next, which turned out to be particularly important on the planar surface we were driving. Additionally, the cameras needed to be pointed so that they do not see the solar

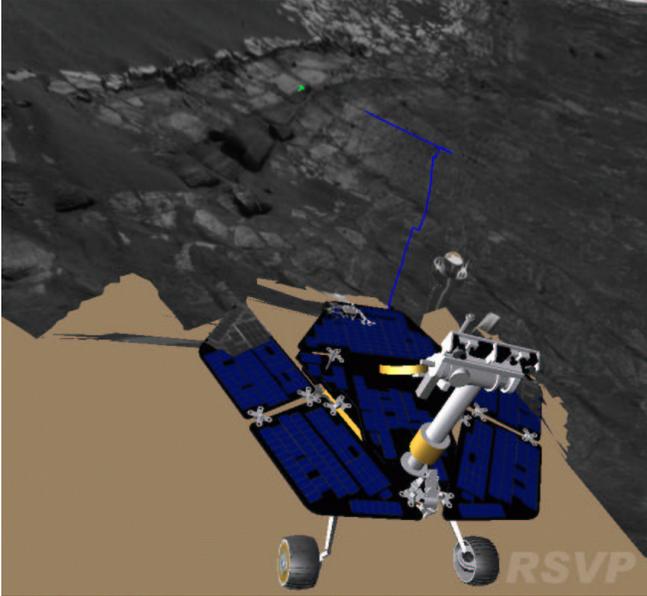


Fig. 7. Sol 304 8 meter drive path (blue line) and IDD goal (green arrow).

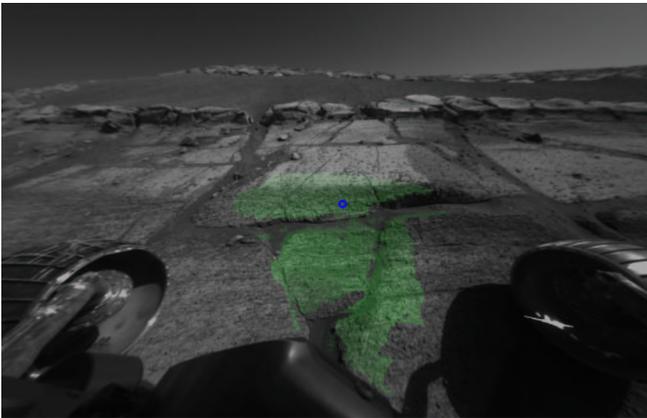


Fig. 8. Sol 304 drive result, green overlay shows IDD reachability.

panels (high reflectivity can cause the images to bloom) or the rover's shadow (which can confuse visodom in smooth terrain). With these constraints, the rover kept track of its position within centimeters over meters of traverse even when slip was high (verified by manual co-registration of images taken of the same terrain from different locations).

We began closing the loop on-board with visodom position estimates by way of conditional ARC commands and TURN_TO commands. But we made sure that if visodom did not converge or converged to a wrong answer, the drive was safe even if all ARC commands were executed. TURN_TO commands were constrained with tighter timeouts.

On the way to Burns Cliff, we stopped to observe an intriguing boulder seen from the crater rim named “Wopmay”. It was a bit taller than the 60 centimeter solar panel ground clearance, so we had to be very cautious around it. The nearby slopes at roughly 20 degrees were not as steep as we had seen at ingress, but the terrain was much softer. We experienced high slip, but after a few sols did get into a good position to observe Wopmay with the IDD. On the drive away from Wopmay, however, we encountered a buried slab of rock. While attempting to climb over the slab, the rover slid laterally along it. The drive sequence was constructed to abort halfway if the rover did not think it was sufficiently close to a waypoint (this would happen either if visodom was not converging or if the slip was larger than predict). This triggered, and stopped execution of the second leg of the drive which, if the rover continued to slide along the slab, could have caused solar panels to hit Wopmay.

For the next several sols, progress uphill was very slow. The rover got bogged down twice in loose sandy terrain. Here as at Eagle crater, driving at roughly 45 degrees to upslope vector was the most effective way to make progress. Once the rover got higher in the crater, we were back on solid rock – and stayed on this “rock highway” high on the crater rim for the rest of our time in Endurance.

We stopped a few meters short of a desired goal named Burns Cliff; close enough to get stunning PANCAM of the region but not close enough to observe with IDD. The terrain ahead was simply getting too steep, and terrain downhill was too treacherous. On sol 295, we began a three week drive to the egress location 10 meters east of where we entered.

We twice saw body tilts as high as 31 degrees during these drives to and from Burns Cliff, but since it was on rock the rover held its traction. We did not push the tilts any higher out of concern that we could lose traction and slide, especially if the bogies articulated again, pushing our body tilt even higher than terrain tilt (similarly, if the downhill wheels buried themselves while uphill wheels were on rock, it would also add to our body tilt). We had to leave ample margin against the approximately 45 degree static stability limit, to allow recovery should a drive go unexpectedly.

A final IDD observation was requested just prior to leaving the crater. As a piece de resistance, we nailed an 8.7 meter approach on a 24 degree slope in a single sol – position estimation error was less than 5 centimeters over that drive. This combined all the techniques we had learned thus far. The drive was done with visodom, and the first half was pure cross slope to get us downhill of the target, followed by a purely uphill drive to the target with conditional ARC's to make use of visodom estimates. Manual slip estimation was still done to determine a reasonable number of conditional ARC's to sequence, and to set bounds for a mid-drive waypoint check.



Fig. 9. *Opportunity* heat shield, impact divot, and nearby small meteorite, imaged on sol 324.

VI. SOLS 316–410+: PLAINS TO VICTORIA CRATER

Our first stop after egress from Endurance was to pause and image the tracks we had laid down six months earlier, driving to and from the second panorama position. We crossed old tracks with new tracks and imaged with both PANCAM and the microscopic imager, and saw a definite dust build-up, consistent with dust build-up seen on the rover deck. We then stopped to examine the heat shield approximately 200 meters south. It had split into two major pieces upon impact, and scattered a few large springs in the area that we did not want to drive over. We circumnavigated the site, and examined both major pieces with the microscopic imager and PANCAM. Amazingly, less than 10 meters away from the heat shield, we found an iron meteorite about 15 centimeters across, the first ever found on another planet.

After examination of tracks, heat shield and meteorite, it was time to continue driving south. The current terrain has long shallow ripples, and periodically flat rocks in the bottom of the troughs between ripples. We are visiting small craters on the way south through terrain that appears rougher and mottled from orbital imagery, and ultimately are aiming for Victoria Crater six kilometers south of Endurance. The small craters are useful landmarks for localizing the rover position in our orbital maps, and we try to hop from one small crater to the next every couple of sols.

In this obstacle-free terrain, we have been able to drive more than 150 meters on a single sol many times, with our current record of 220 meters set on sol 410. We are making use of the suspension articulation fault protection, which stops driving should either the bogies or differential angles exceed programmable limits. We begin with a longish blind drive with loose suspension limits, then do a “bonus” blind drive that has tight limits, and finally autonav. Should these limits stop the drive early, the sequence conditionally recovers by clearing errors, widening the limits, backing up, and starting the autonav portion early. We have also done multi-sol drives, where the first sol starts with a standard long blind drive, followed by autonav. Subsequent sols pick up with continued autonav drives. Using this technique we have driven 400 meters over 3 sols in a single planning cycle.

VII. CONCLUSION

Exploring Meridiani Planum with *Opportunity* has been a constant source of challenge and excitement, from studying the outcrops at Eagle Crater, traversing both the rim and inside of Endurance Crater, examining the heat shield, and imaging the troughs and small craters that dot the plains.

As of sol 410, *Opportunity* is about one third of the way from Endurance Crater to the much larger 750 meter diameter Victoria Crater 4 more kilometers to the south. We cannot wait to see what the Etched Terrain, intermediate craters and fissures, and Victoria Crater have in store for us.

VIII. ACKNOWLEDGEMENTS

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