Mars Curiosity Rover Mobility Trends During the First Seven Years

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Abstract

NASA's Mars Science Laboratory (MSL) Curiosity rover landed on Mars on August 6, 2012. In the seven years between landing and August 6, 2019 (sol 2488), Curiosity has driven 21,318.5 meters over a variety of terrain types and slopes, employing multiple drive modes with varying amounts of onboard autonomy. Curiosity's drive distances each sol have ranged from its shortest drive of 2.6 centimeters to its longest drive of 142.5 meters, with an average drive distance of 28.9 meters. Real-time human intervention is not possible during Curiosity's drives due to the latency in uplinking commands and downlinking telemetry. Instead, the operations team relies on Curiosity's fault protection, Autonomous Navigation, and Visual Odometry software to keep the rover safe during drives. During its first seven years on Mars, Curiosity has attempted 738 drives. While 622 drives ran to completion, 116 drives were prevented or stopped early by Curiosity's fault protection software. The primary risks to mobility success have been wheel damage, wheel entrapment, progressive wheel sinkage, and the potential for hardware or cable failures that result in an inability to command one or more steer or drive actuators. In this paper, we describe Curiosity's mobility subsystem, mobility trends over the first 21.3 km of the mission, operational aspects of mobility fault protection, risks to continued mobility success, and risk mitigation strategies.

1 Introduction

On August 6, 2012, the NASA Mars Science Laboratory (MSL) Curiosity rover landed on Mars and began the surface phase of its mission. Seventeen Martian solar days (sols) later, Curiosity executed its first drive of 7.005 meters. Curiosity was designed to survive at least one Mars year (approximately 23 Earth months) and drive at least 20 km. August 6, 2019 (sol 2488) marked the seven-year anniversary of the landing of Curiosity on Mars. Curiosity has driven 21,318.5 meters over those years, exceeding the 20 km design goal. Thus far, Curiosity has achieved 47.2% of the total odometry achieved by the solar-powered Mars Exploration Rover (MER) Opportunity, which holds the record for off-Earth wheeled vehicle odometry at 45.16 km, achieved over its 14.375 years of operation between January 25, 2004 and June 12, 2018. MSL's mobility-related mission peak records are shown in Table 1.

The goal of the MSL mission is to explore and quantitatively assess the habitability and environmental history of the Gale crater field site, which includes the landing ellipse and the adjacent lower portion of Mount Sharp (Grotzinger et al., 2012). Figure 1 shows the route that Curiosity has driven since it arrived at the Bradbury Landing site. On sol 2481, Curiosity arrived at Glen Etive, its location at the seven-year anniversary of its landing. Curiosity remained

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parked at Glen Etive until sol 2555 during a drill sampling campaign. Figure 2 contains a selfie of Curiosity at Glen Etive, generated from dozens of images acquired by the Mars Hand Lens Imager (MAHLI) mounted to the robotic arm turret.

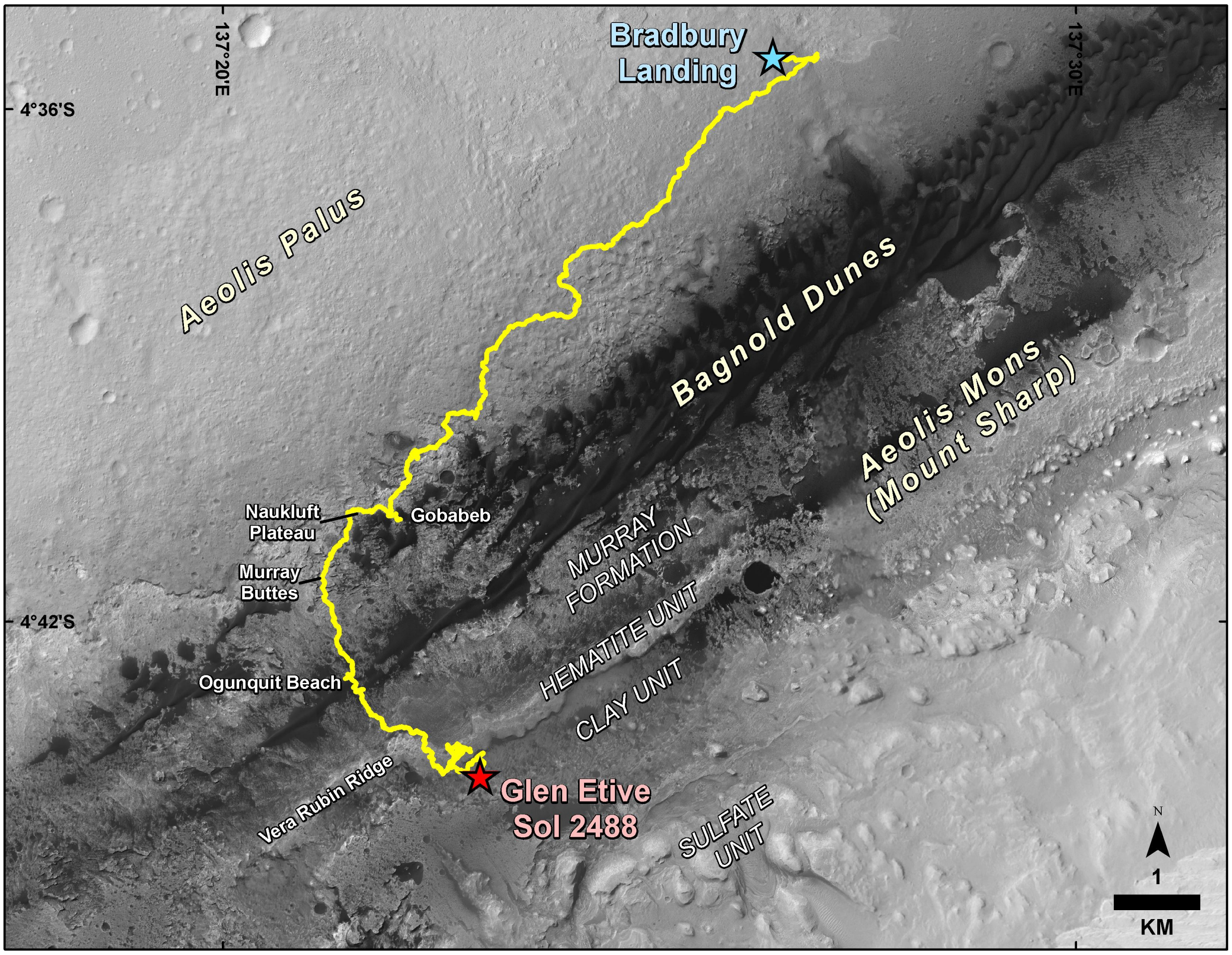

Figure 1: This map shows the route driven by NASA's Curiosity Mars rover, from its August 2012 landing through August 2019. The blue star near the top center marks "Bradbury Landing," the site where Curiosity arrived on Mars on August 5, 2012, PDT (August 6, EDT and Universal Time). Curiosity landed on Aeolis Palus, the plains surrounding Aeolis Mons (Mount Sharp) in Gale Crater. The base image for the map is from the High Resolution Imaging Science Experiment (HiRISE) camera on the Mars Reconnaissance Orbiter. Image Credit: NASA/JPL-Caltech/Univ. of Arizona.

As illustrated in Figure 3, much of the driving to the lower layers of Mount Sharp has been uphill. As of sol 2488, 60.75% of Curiosity's driving has been uphill, resulting in a total increase in elevation of 418.4 meters. During the MER mission, the maximum increase in elevation by Opportunity was 347.6 meters, which occurred on sol 4663. Comparing cumulative odometry and change in elevation for Curiosity and Opportunity at the seven year mark for each mission, Opportunity had driven 5.34 km further, but Curiosity has climbed 277.3 meters higher. Mobility choices are guided by each mission's long term strategic science plan, but are subject to changes due to near term science objectives and engineering constraints arising from terrain features not evident from orbital planning images.

Curiosity has driven over a variety of terrain types and slopes, employing multiple drive modes with varying amounts of onboard autonomy including Visual Odometry (VO), Hazard Detection, Hazard Avoidance, and Visual Target Tracking (VTT). Real-time human intervention during Curiosity drives is not possible due to the latency in uplinking commands and downlinking telemetry. The inherent delay in radio communications due to the distance between Mars and Earth can vary from 8 to 21 minutes each way depending on their orbital configuration, and the use of Mars orbiters to relay

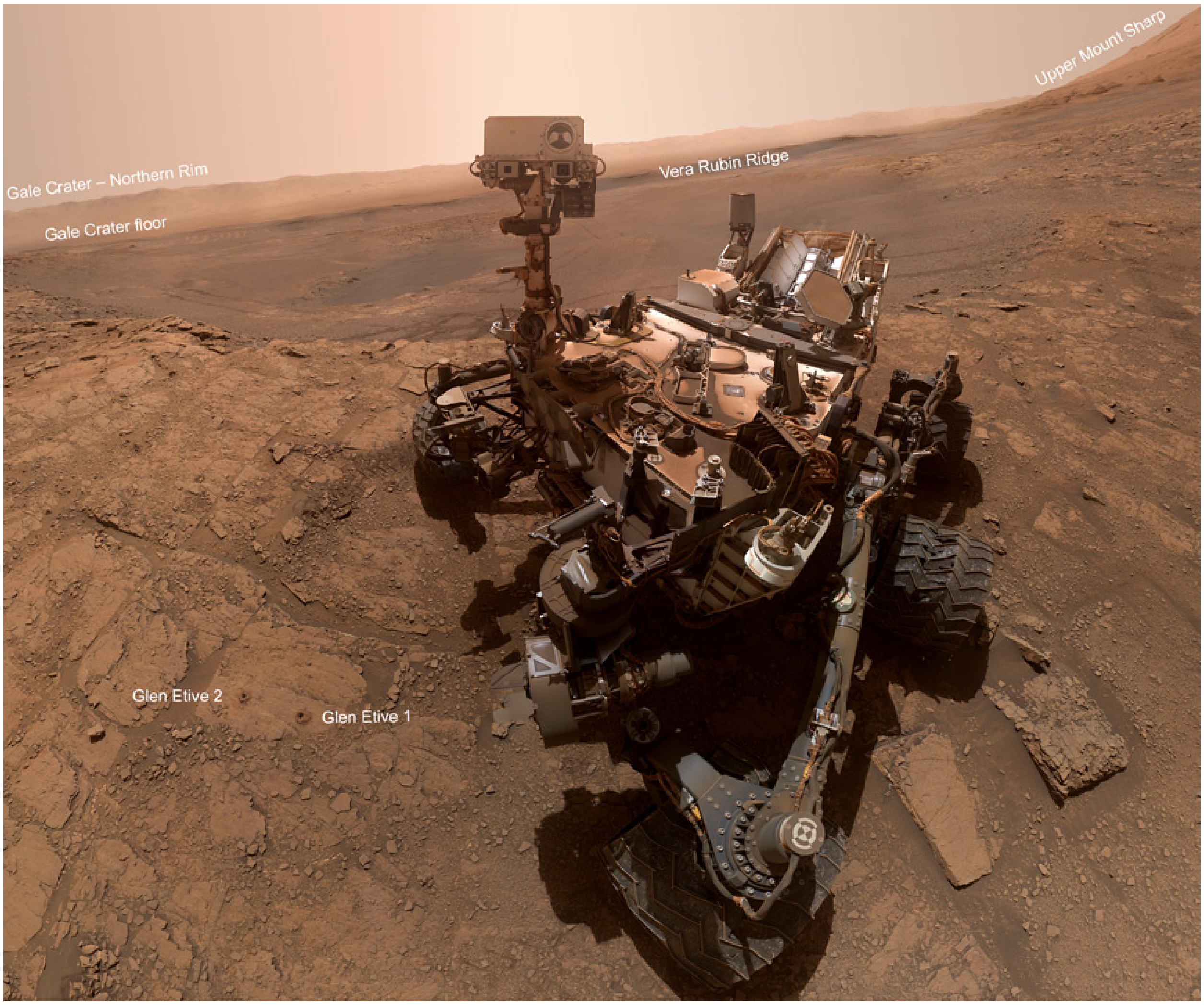

Figure 2: Curiosity selfie image acquired on October 11, 2019 (sol 2553) at Glen Etive, where Curiosity drilled two holes. This selfie was generated by stitching together 57 individual images acquired by the MAHLI, a camera on the robotic arm turret. The robotic arm, which acts as a selfie stick, is not visible in the image. The Remote Sensing Mast, which contains navigation cameras, is mounted to the right side of Curiosity. Image Credit: NASA/JPL-Caltech/MSSS.

information at higher bandwidths can introduce further latency. So the MSL operations team relies on Curiosity's fault protection software to prevent the rover from driving into an unsafe state during drives. When fault protection software detects or predicts a state unsafe for driving, an error is declared which halts the rover and prevents future driving. The thresholds for tripping fault protection are parameters that are set by human Rover Planners (RPs) for each drive or drive segment, based on high-resolution imagery of the path ahead and review of recent drive performance in nearby terrain.

During Curiosity's first seven years on Mars, 738 drives planned by the MSL operations team were successfully uplinked to Curiosity; 622 of those drives successfully completed with the rover reaching its goal position. Of the 116 drives that did not run to completion, 53 were terminated early due to 8 types of system fault protection unrelated to mobility, and 63 were terminated early by 16 types of mobility fault protection. Despite 15.7% of its attempted drives terminating early, Curiosity has achieved 91.7% of its attempted odometry.

Driving through unknown terrain can present challenges to the operations team. Curiosity has experienced a significant amount of wheel damage to the left front and middle wheels, and in response, a software patch was installed on

Curiosity to perform terrain-adaptive wheel speed control (TRCTL). Other risks to continued mobility success include: reductions in available power that may limit drive time, unsafe terrain that may limit drive distance, a drive or steer actuator hardware failure, a computer or engineering camera (ECAM) failure, wheel sinkage, driving under an unknown unsafe condition, wheel entrapment, a rock wedged between two wheels, rover tip over, rover high centering, suspension hardware failure, mobility heater or thermometer failure, hardware failure of the rover inertial measurement unit (IMU), and loss of calibration of a camera used for wheel slip and/or terrain hazard assessment.

In this paper, we describe Curiosity's mobility system, VO performance, commandable drive modes, mobility fault protection, drive and steer actuator health, wheel health, risks to continued mobility success for the remainder of the mission, and risk mitigations. We will use VO to refer to the vision-based system for determining accurate position information, Wheel Odometry to refer to position estimates updated at 8 Hz while in motion that assume no slip, and just "odometry" to refer to overall distance covered while driving, regardless of whether VO was explicitly enabled. An earlier version of this paper appeared as (Rankin et al., 2020).

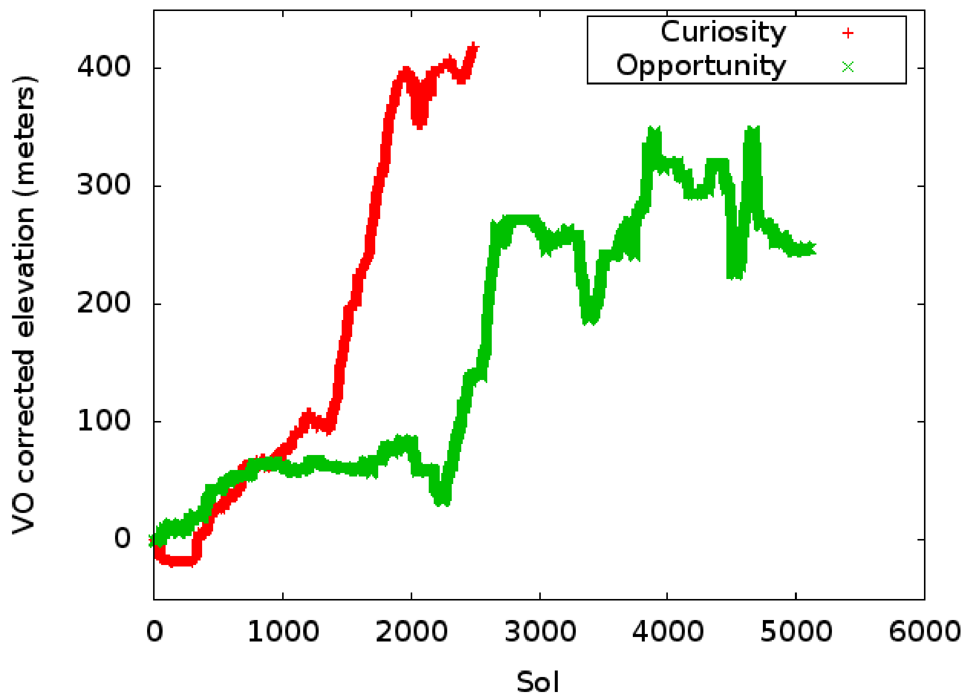

Figure 3: Change in rover elevation for Curiosity over the first seven years of its mission, and Opportunity over its 14.375 year mission. A Mars solar day (sol) is approximately 39 minutes and 35 seconds longer than the 24 hour Earth day.

2 Mobility System

Curiosity's mobility system consists of the wheels, drive and steer actuators and encoders, suspension, IMU, and the flight software related to mobility and navigation of the rover (which also makes use of ECAMs for terrain understanding and VO measurements). Curiosity's IMU contains three fiber-optic gyros and three silicon micro-electromechanical system accelerometers. The ECAMs consist of two stereo pairs of navigation cameras (NavCams) on the Remote Sensing Mast (RSM), which is mounted to the the right side of the rover, two stereo pairs of hazard cameras (HazCams) mounted to the front of the rover, and two stereo pairs of HazCams mounted to the rear of the rover (Maki et al., 2012).

Like the Mars Exploration Rovers (MER), Curiosity is a six-wheeled rover with a rocker-bogie suspension. The six wheels are identical. They are constructed of aluminum (for its light weight), and have a width of 40 cm and a diameter

Table 1: Curiosity mobility-related mission peaks during the first seven years

Data Types	**Sol**	**Value**
Max rover pitch	2476	25.22°
Max rover roll	2047	20.69°
Max rover tilt	2477	25.34°
Longest drive on RCE-B	665	142.498 meters
Longest drive on RCE-A	2221	59.428 meters
Max number of VO failures in one sol	2434	11
Max rover slip	2087	98.7%
Max wheel slip	2087	98.7%
Max differential angle	1371	9.40°
Max bogie angle	1473	-21.30°
Max non-startup drive current	1587	4.422A (right rear wheel)
Max non-startup steer current	1616	3.439A (right rear wheel)
Max drive current	1587	4.422A (right rear wheel)
Max steer current	494	3.594A (left front wheel)

Table 2: Key Curiosity Wheel and Steer Actuator specifications

Specification	**Value**
Gear ratio	1024:1
Encoder ticks per motor revolution	144
Encoder ticks per output revolution	147,456
Encoder accuracy	0.0024°/tick (not including backlash)
Encoder sampling rate	64 Hz
Max current	10 A
Max wheel angular rate	+/-9.63°/s
Max wheel linear speed	4.2 cm/s

Table 3: Key Curiosity suspension resolver and IMU specifications

Sensor	**Sampling rate**	**Accuracy**
Resolver	64 Hz	0.51°to 0.65° (experimentally measured)
LN-200 IMU	8 Hz	Not published

Table 4: Key Curiosity ECAM specifications related to mobility. All ECAM stereo pairs have backup cameras, but only the two pairs of rear HazCams are mounted on opposite sides of the rover (left side for RCE-A, right side for RCE-B).

Cameras	**Field of View**	**Sensor Resolution**	**Location**
NavCams	45°x 45°	1024 x 1024 or 256 x 1024	Forward right corner mast
Front HazCams	124°x 124°	1024 x 1024 or 256 x 1024	Center of front body panel
Rear HazCams	124°x 124°	1024 x 1024 or 256 x 1024	Outside of rear body panel

of 50 cm. The six wheels are named left front (LF), left middle (LM), left rear (LR), right front (RF), right middle (RM), and right rear (RR). The MSL wheel design is detailed in (Haggart and Waydo, 2008).

Curiosity's rocker-bogie suspension system is similar to the Mars Sojourner rover (Bickler, 1998) and MER (Harrington and Voorhees, 2004). There is no motorized actuation in the rocker-bogie suspension system. Changes in the suspension occur passively in response to the wheels' interaction with terrain. The primary benefit of the rocker-bogie suspension system is its ability to keep the tilt angle of the rover body low when individual wheels encounter tall terrain features, reducing the risk of rover tip-over. The rocker arm rotates about the differential pivot, and the bogie arm rotates about the bogie pivot. Resolvers measure the bogie and differential angles at 64 Hz. The accuracy errors of all of Curiosity's suspension resolvers were experimentally determined (using an absolute encoder) to be within the range of 0.51°to 0.65°.

A differential angle increases when the corresponding front wheel is climbing, and decreases when it is descending. A bogie angle increases when the corresponding middle wheel is climbing and/or the rear wheel is descending. A differential bar across the top of the rover body connects to the left and right rocker arms through short links and rotates about the Center Differential Pivot (CDP), constraining the left and right differential angles to have the same magnitude but be oppositely signed.

There are ten identical wheel and steer actuators (WSA) on the Curiosity rover. Six of the WSAs are mounted in the hub of each of wheel, and enable driving by rotating each wheel independently about its horizontal axis. Four of the WSAs are mounted above the front and rear wheels to enable steering by rotating each wheel independently about its vertical axis. The middle wheels are not steerable. The mobility subsystem is illustrated in Figure 4 and key specifications are included in Table 2, Table 3, and Table 4.

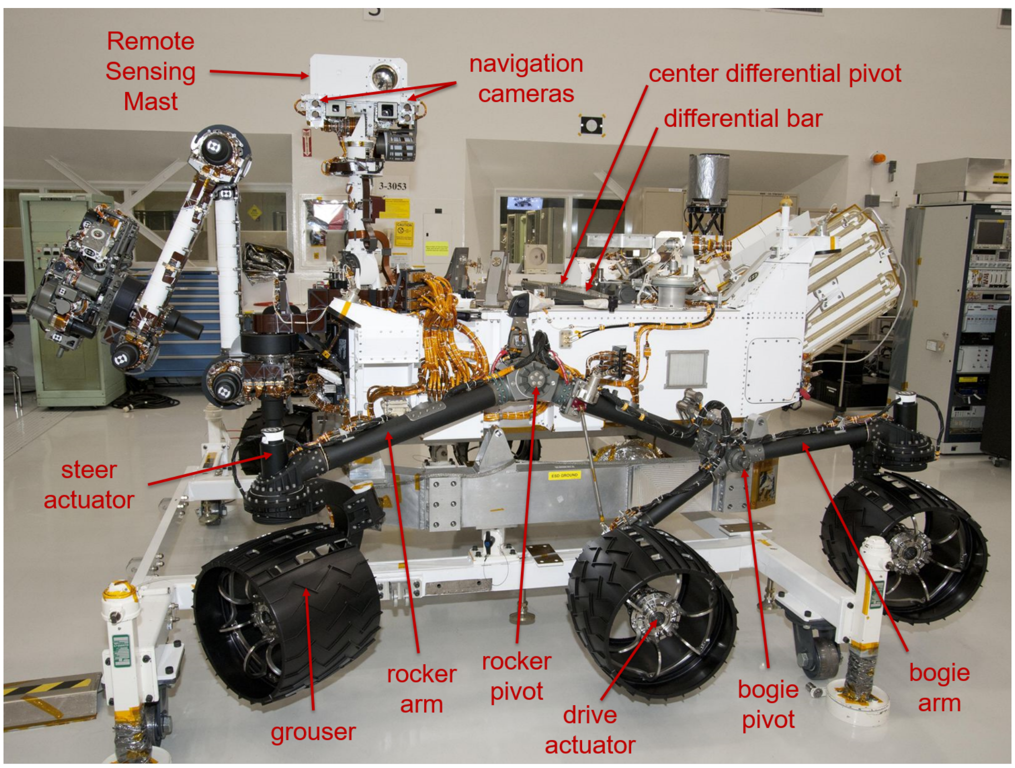

Figure 4: Curiosity in the Jet Propulsion Laboratory (JPL) Spacecraft Assembly Facility. The mobility system consists of six identical aluminum wheels, six drive actuators, four steer actuators, an IMU (mounted inside the rover body), a rocker-bogie suspension, and the flight software related to mobility and navigation, which makes use of ECAMs.

Each WSA contains a brushless, direct current (DC) motor with 1024:1, 4-stage, planetary gear reduction, a brake, and a incremental encoder. Each WSA can handle 10A of current and can generate 1000 Nm of torque. In practice, the drive and steer currents are much lower than 10A. The max WSA current during the first seven years of the mission has been 4.422A. Software current limits for each actuator are specified by setting parameters. The current limits for the drive and steer actuators have been set to 5.25A and 4.5A, respectively. The average motor current and current standard deviation of each WSA are discussed in the Section 8.

Curiosity's motor controller assembly (MCA) has eight motor controller driver (MCD) boards. Therefore, up to eight of the thirty-eight rover motors can be simultaneously controlled. Since Curiosity has ten WSA, all of the WSAs cannot be simultaneously controlled. Due to this limitation, which arose during the avionics design of the motor control board accommodation strategy, a steer-then-drive architecture is used. Steer relative encoders are not monitored during driving and drive relative encoders are not monitored during steering. In addition, any mobility motor motion that occurs after a mobility command completes is not measured by WSA encoders.

Curiosity executes drive steps primarily using two drive primitives; an arc and a turn-in-place maneuver. Arcs are specified with an arc length and the desired change in heading, or delta heading. Straight arcs are specified with a delta heading of zero. Arc commands are executed open-loop, i.e., their termination does not depend on reaching a heading or position. An arc command is executed by steering first, if needed to achieve the commanded curvature, then driving the wheels until half of the wheels have turned the pre-determined amount needed for ideal planar terrain.

As shown in Figure 5, most of Curiosity's commanded arcs have been straight (81.0%) or with a shallow curvature. The arc with the largest commanded delta heading was on sol 595; a backwards arc with an arc length of 3 meters and a delta heading of 120°was commanded mid-drive when transitioning from forward driving to backward driving.

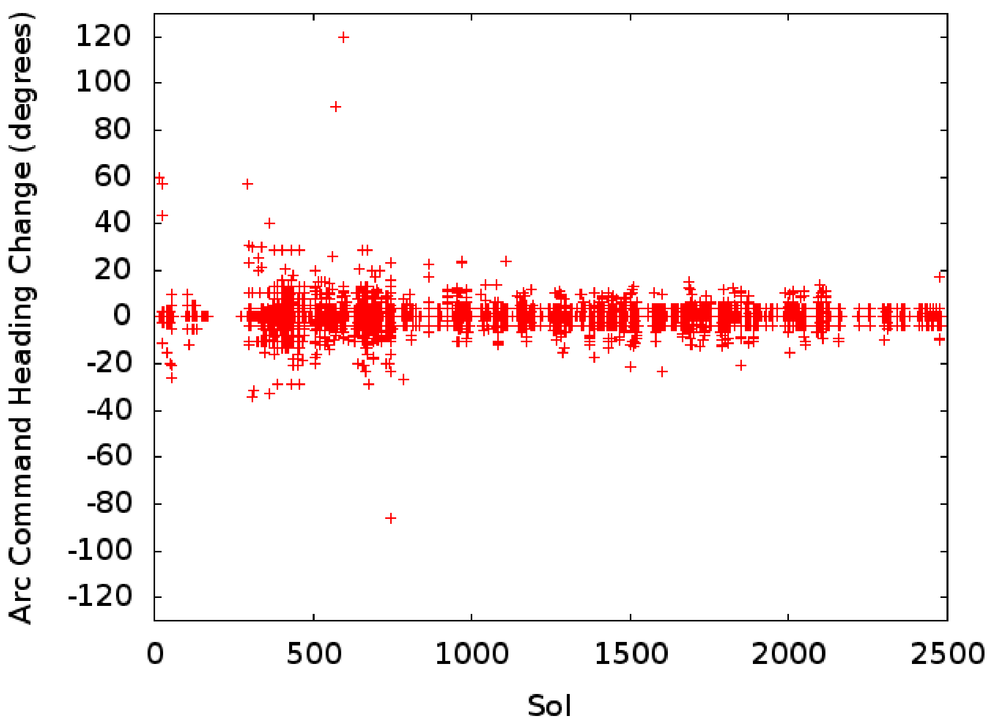

Figure 5: Arc drive steps are specified by an arc length and change in heading. This plot contains the commanded heading change for all 22,312 commanded arc drive step during the first seven years of the mission. Most of the commanded arcs have been straight (81.0%) or with a shallow curvature.

Some heading error (i.e., unintended yaw) inevitably occurs during constant curvature arc driving, the extent of which depends on rover tilt, the wheel/terrain interaction, and whether TRCTL is enabled. Curiosity's flight software (FSW) was updated to version R11 on sol 482, and included an enhancement that calculates heading error statistics for straight arcs onboard, and reports them in telemetry for each drive step. Figure 6 shows the mean heading error and standard deviation of heading error for the straight arcs that were executed beginning on sol 482. Nominal use of TRCTL began on Sol 1678, and the reduction in both the mean of the absolute value of the mean and standard deviation of the heading error for straight arcs since then has been 41%.

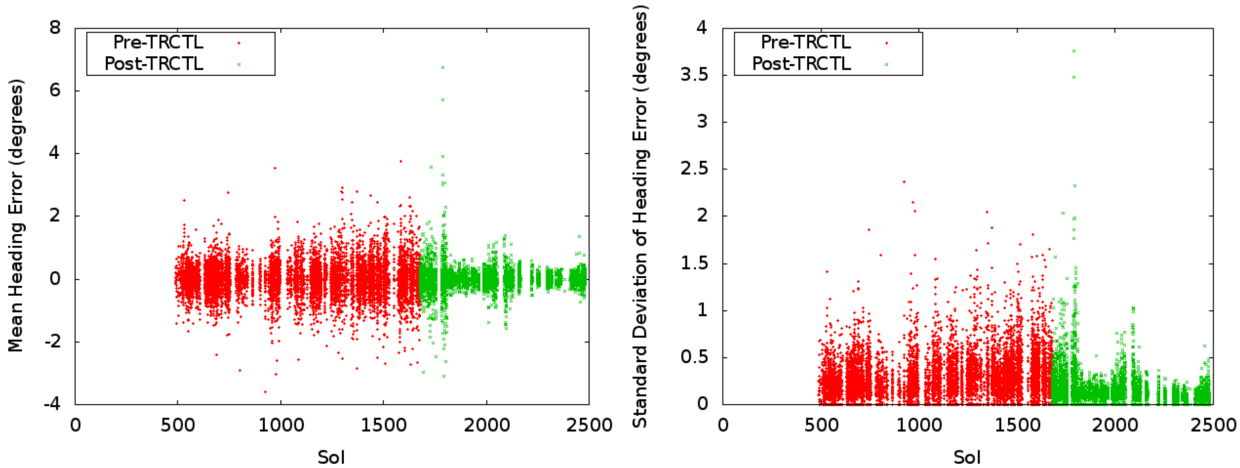

Figure 6: Mean heading error (left) and standard deviation of heading error (right) for each executed straight arc beginning on sol 482, when Curiosity's flight software was updated to include this data in telemetry. The number of straight arcs executed between sols 482-1677 (pre-TRCTL) and sols 1678-2488 (post-TRCTL) were 9,990 and 4,840, respectively. The average number of samples for each straight arc executed between sols 482-1677 (pre-TRCTL) and sols 1678-2488 (post-TRCTL) were 215.0 and 210.4, respectively. The spike on sol 1789 to 6.75°occurred due to the right wheels being in sand and the left wheels being on firmer terrain. Wheel slip reached 78.3% and the rover heading change caused the yaw limit to be exceeded, stopping the drive early.

Turns-in-place can be specified using an arc length of zero, but in practice are typically commanded using specialized closed-loop turn commands that only terminate when the desired heading has actually been achieved, as measured by the IMU. Figure 7 contains a plot of the commanded heading change for three types of closed-loop turn-in-place commands; 1) a turn relative to the current heading, 2) a turn to an absolute heading, and 3) a turn to face a navigation goal or a specified offset from a navigation goal. Turning to face a navigation goal or offset from a navigtion goal is the most used turn-in-place command, accounting for 75.2% of the total magnitude of turn commands. They are typically commanded after arriving at a waypoint to point the rover towards the next waypoint. Turning to an absolute heading is common at the end of a drive to orient the rover at a heading optimal for transmitting telemetry to a Mars orbiter or direct to Earth (DTE), accounting for 17.0% of the total magnitude of turn commands. Several large magnitude turns were performed during the period between sol 500-650 when there was an increase in the usage of backwards driving.

In addition to these basic commands, the rover also accepts a high-level command to drive to a nearby waypoint. The surface navigation flight software autonomously selects an arc or turn to execute as the next step toward the waypoint goal. During steps requiring steering, the steering actuator brakes are released, the front and rear wheels are steered to appropriate steer angles, the steering actuator brakes are engaged, then the drive step is executed.

3 Visual Odometry

Maintaining an accurate pose estimate yields many operational benefits for mobility. When human operators create a drive plan for a given sol, they often specify terrain features like drive goals and hazard locations in map coordinates (expressed in a local "Site frame"). So it is important for the rover to know where it is within that frame, to stay safe and know when it has reached its desired goal location. Curiosity nominally uses its IMU to sense attitude changes at 8 Hz, wheel odometry to estimate its distance traveled at 8 Hz, and VO flight software to measure actual changes in position less frequently. The wheel-based distance vector is added to the current position by projecting it forward according to the current gyro-based attitude. Other configurations are possible in the event of component failure, but this is the mode that has been used for the period presented in this paper. Since VO works by tracking terrain

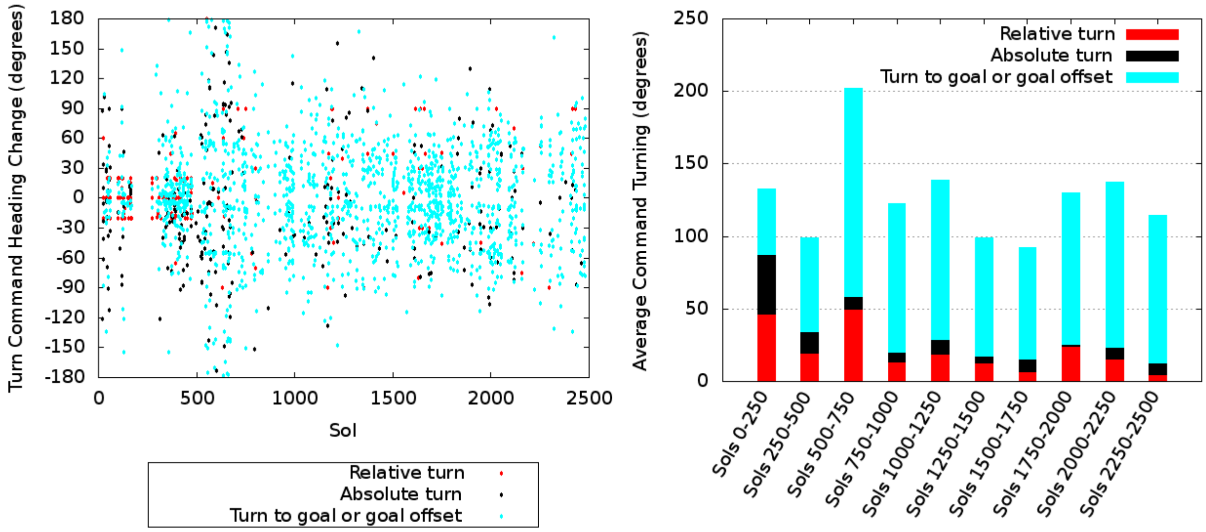

Figure 7: Commanded heading change for all of the closed-loop turn-in-place commands (left) and average command turning for sols that included closed-loop turn-in-place commands (right). The percentage of the total magnitude of relative, absolute, and turn to goal or goal offset turn commands are 7.8%, 17.0%, and 75.2%, respectively. For the average command turning plot, a 250 sol interval was arbitrarily selected. Decreases in average command turning have been temporary.

Table 5: VO statistics during the first seven years of the mission

Activity	**Count**
Drive sols using VO	692
VO attempts while driving	20,682
VO convergences while driving	20,588
VO failures reported	94
VO failures caused by FSW	66
Average VO attempts per drive sol	29.86
Number of drives stopped by VO failures	5

features, there must be enough overlap between images to enable tracking of dozens of features. Most drives plan to achieve 60% or more overlap between images, typically stopping every 1 meter to acquire and process new image pairs. NavCams have 45°fields of view, and are located on the pointable RSM at 1.96 meters above flat ground. During VO drives they are typically pointed down between 20-30°in elevation, and their azimuth can vary by nearly 180°. Normally RPs point them either to the right or forward, depending on the local terrain feature availability and rover shadow predictions, but they can also be pointed at a particular locations in Site frame.

Table 6: VO failures by category

Failure Type	**Count**
VO failed to converge	66
Step truncation reimaging failure	12
Sequencing failure	10
Strategy failure	3
IMU parameter failure	3
Total	**94**

Curiosity's VO capability built on the success of the MER Visual Odometry algorithm (Maimone et al., 2007a), updating the algorithm and improving its performance (Johnson et al., 2008). The technique works by comparing pairs of stereo images taken in the 45°FOV navigation cameras (Maki et al., 2012) before and after a relatively short drive step, typically one meter apart. Terrain features are discovered and tracked autonomously, and the resulting motion vectors are processed yielding a 6-DOF pose update. So long as enough features are found and multiple internal sanity checks all pass, the position part of the update is incorporated back into vehicle's current position estimate. Although VO computes both attitude and position updates, the IMU attitude solution has performed well during the first seven years (as witnessed by even long-range drives achieving their specified goals), so only VO position updates have been configured for use.

As illustrated in Figure 8, Curiosity VO position accuracy is better than 1 mm when the NavCams are pointed in the default VO direction (to the right and down), there are no shadows of the rover in the VO images, and consecutive NavCam images are used for the VO update images. The steady accumulation of position error in the right plot (with correlated direction in the left plot) is likely attributable to the fact that we ran VO in a special "Keep Seed" mode for this test; instead of comparing the most recently acquired pairs of images, we compared each new image pair against the very first one taken. As a result the micro-shadows generated near small pebbles moved with the Sun in the update image but not the seed image, causing the sub pixel location of some highest contrast update features to move as well. The increased error is therefore likely attributable to this unmodeled shadow motion at a small scale (see the difference image in the lower right of Figure 8). In total, 141 measurements were made using images spanning 5429 seconds from 11:40:45 to 13:08:49 in Mars local time.

3.1 Measuring Slip

Another benefit of VO is that it is the only system on the rover that can provide positional slip estimates with sufficient precision. Although in theory one could attempt to derive a position estimate by doubly integrating accelerometer measurements, in our system those readings are often too noisy to provide useful data directly. See Figure 9 for a comparison of rover tilt values derived from accelerometers vs those derived from gyros on a particular sol.

Using VO, we compute two slip fraction estimates onboard, rover slip and wheel slip.

Wheel Slip Fraction is the sum of the linear distances of all VO-corrected wheel positions from what their idealized/no-slip positions would be, divided by the summed wheel pathlengths driven since the prior VO initialization/update. This definition is valid for all basic motions including turns in place.

Rover Slip Fraction is the Euclidean distance between the initial (idealized/no-slip) and VO-corrected positions of the rover origin (located at the rover's turning center between its middle wheels), divided by the idealized/no-slip pathlength the rover origin has taken since the prior VO initialization/update. Note that this is undefined (and therefore not computed) during turns in place.

Table 7: Overall Mission Slip Statistics (max slip from sol 2087)

Category	**Percentage**
Average of max rover slip per sol	16.69%
Average rover slip	6.24%
Average wheel slip	8.44%
Max rover slip	98.70%
Max wheel slip	98.70%

For example, a wheel slip fraction of 0.0 means there was no slip; VO confirmed the rover was at its estimated no-slip position. On the other hand, if the rover commanded a straight arc but VO determined it did not move at all, the wheel slip fraction would be 1.0.

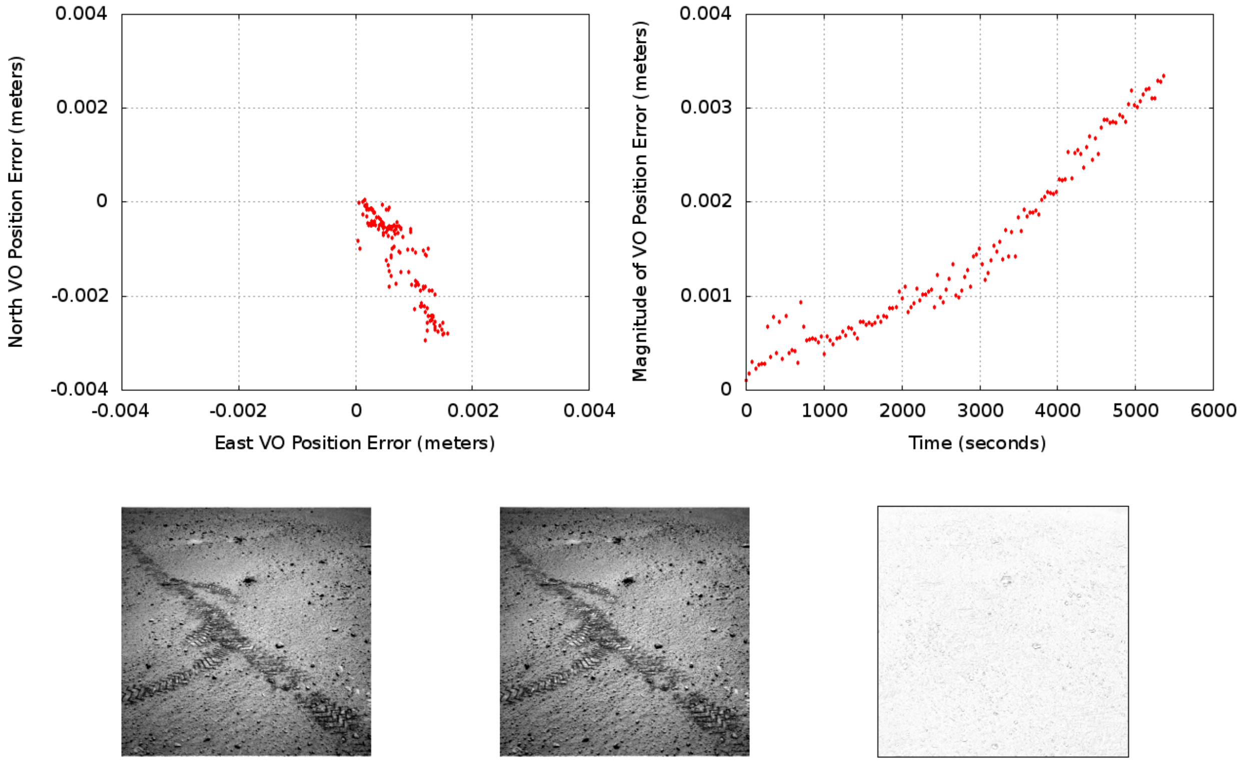

Figure 8: On sol 571, VO was performed 141 times over a 90.5 minute period with Curiosity and the RSM stationary. The NavCams were pointed in the default VO direction (to the right and down) and the test was performed at a time when the terrain in the VO direction was not in the rover's shadow. For this period, the rover pose was not updated after each VO step; VO was used to monitor the rover state during drill operations, and would have halted drilling had excessive slip been detected. Each VO step used the initial VO seed image. The average 3D VO position error was 1.5 mm with a standard deviation of 0.9 mm. VO 3D position error increased generally linearly with the time between the VO seed image and the VO update. During drives, consecutive NavCam images are used for the VO seed and update images, acquired approximately 1 minute apart, depending upon the selected drive step distance. The graphs in the top row show the position error location offsets and magnitude, respectively. The images in the bottom row are the seed image from 11:40:45 Mars local time, the update image from 13:08:49 Mars local time, and a difference image showing the absolute value of each pixel's intensity difference between those two images, illustrating the small shadow changes that resulted from the Sun's motion.

To avoid spurious faults due to high relative slip on very short drives, slip fractions are only generated onboard when the path length between VO updates exceeds a minimum threshold, nominally 0.35 meters. Our fault responses can be configured to use either slip measurement, but we have only used Wheel Slip because it is well-defined for all motions.

Excessive slip is one of the many possible mobility faults that can terminate a drive early. RPs (i.e., those members of the operations team responsible for creating mobility, arm and turret command sequences daily) determine the maximum allowable slip each sol, expressed in two sets of limits. The VO slip "Fast" limit is a slip fraction threshold which, if exceeded, will cause the rover to stop immediately. The VO slip "Slow" limit is a slip fraction and a persistence number; if the "Slow" limit is exceeded for the persistence number of contiguous updates, then a fault will be raised.

Overall slip statistics are given in Table 7, and a plot of the slip fractions measured over the entire mission in Figure 10.

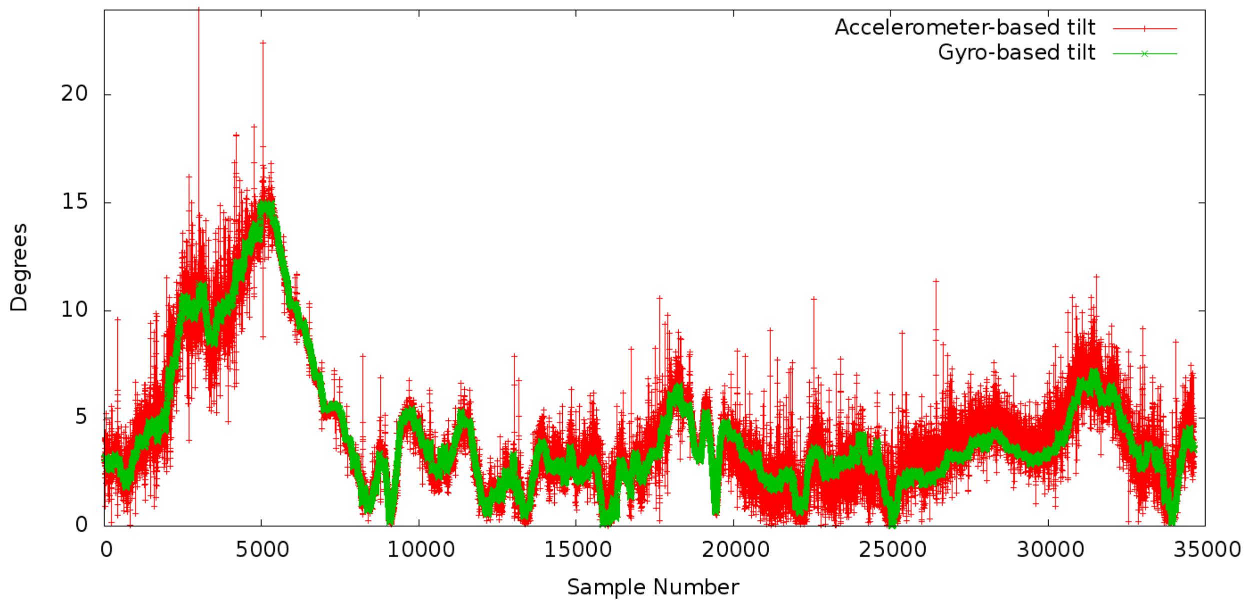

Figure 9: Example comparison of gyro-based tilt estimates vs accelerometer-based tilt estimates from the longest drive on sol 665 (shown in Figure 22). The X axis is the number of the tilt sample collected (at 8 Hz) during all driving, the Y axis is the overall vehicle tilt. The green points are tilt estimates generated by integrating IMU gyro readings over time, the red points are tilt estimates derived from the instantaneous accelerometer readings. Gyro readings are far more stable, because unlike accelerometers they are not influenced by outside forces acting on the rover (e.g., wheel drops off small rocks, compression and release within the rover suspension).

3.2 Visual Odometry Fault Categorization

RPs decide where to point the VO cameras during each drive step, to maximize the likelihood of VO being able to converge on a solution by ensuring sufficient overlap between adjacent VO image pairs. They are aided in this task by planning tools that evaluate overlap in the drive plan (Maimone et al., 2018), but still need to know if convergence failures occur. So it is important to provide feedback to the planning team whenever VO fails to converge on a motion estimate, since that knowledge can help improve results for the future drives.

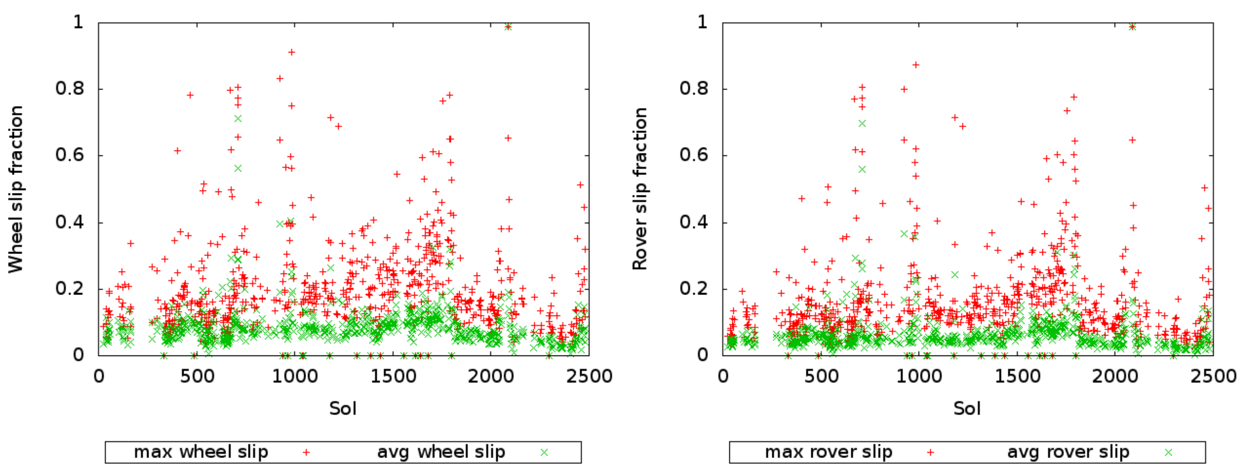

Figure 10: Rover and wheel slip fraction. Slip can vary widely over a drive as rover tilt and terrain type changes.

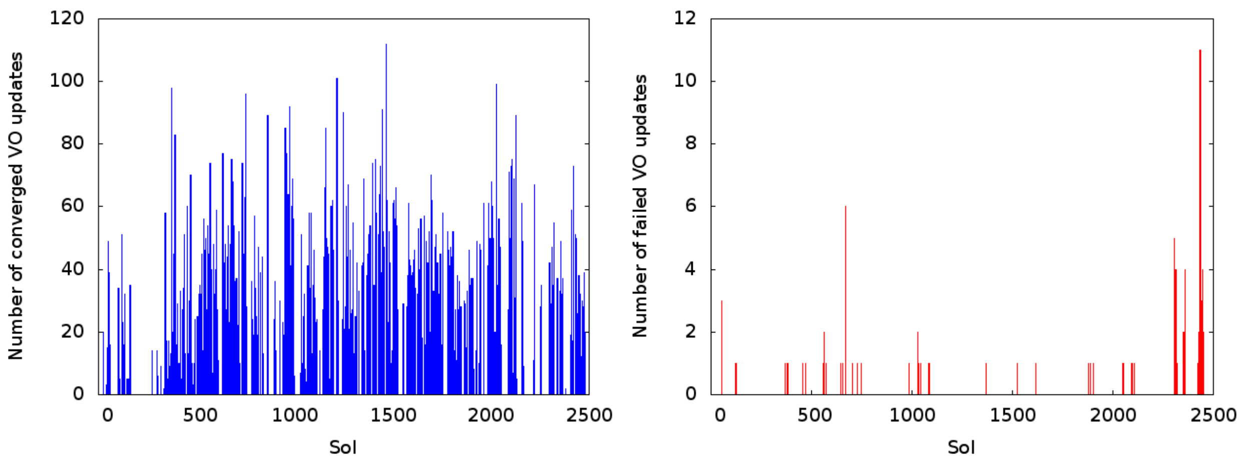

Figure 11: As of sol 2488, VO has been performed 20,682 times during mobility activities with only 94 failures. The max VO failures in a single drive was 11, occuring on sol 2434. Because the terrain surrounding the planned drive was feature-poor, a high number of VO failures was anticipated. The max number of VO failures was set to 10. When the 11th VO failure occurred, it set a mobility goal error, stopping the drive 2.82 meters short of the predicted odometry.

During mobility operations on Mars thus far, MSL VO has successfully converged to a solution 20,588 times out of 20,682 attempts, yielding a remarkable success rate of 99.55%. See Figure 11 for a per-sol breakdown and Table 5 for additional overall statistics. These numbers do not include VO use during non-mobility activities. The different categories of VO failures that have occurred are summarized in Table 6 and Figure 12. The five categories from that table are:

VO failed to converge The majority of failures (66) were due to the algorithm failing to detect enough self-consistent features to be confident in its estimate and thus failing to converge on a solution; that often happens when the cameras are pointed at all-sandy terrain with few obvious unique features, for instance.

Step truncation reimaging failure When driving to a goal location, the rover may autonomously command a turn so sharp that there would be little or no overlap between VO image pairs. Although the FSW was designed to recognize that possibility and automatically truncate any large steps to enable VO to keep working, a bug in the FSW prevented VO reimaging from occurring in those cases. A fix has been developed and is being considered for uplink.

Sequencing failure RPs sometimes realize during plan construction that their command sequences may result in VO failing to converge, but decide to send them anyway (e.g., on the last leg of a drive if precise localization is not required). Or they may send commands outside the normal recommended bounds (e.g., driving a longer distance between image pairs).

Strategy failure Sometimes a fault unrelated to VO causes a mobility command sequence to stop executing. In that off-nominal case, VO can sometimes accidentally try to match images with completely different pointing configurations, resulting in a failure to converge. But since the original plan did follow the best practices, we categorize these as strategic failures rather than sequence failures.

IMU parameter failure On sols 122, 123, and 124, one of the built-in sanity checks triggered, forcing one VO estimate to be rejected each sol. The check was that the VO attitude estimate should match the IMU-generated one within 1°in roll, pitch, and yaw, and each time, the pitch estimate differed by more than 1°(-1.391, -1.072, -2.195°, respectively). Subsequent investigation led to the conclusion that the VO update was actually correct, but there was a bug in the IMU parameter settings (subsequently fixed) that inadvertently dropped attitude updates under high acceleration. Figure 13 shows that there has been little disagreement since those events.

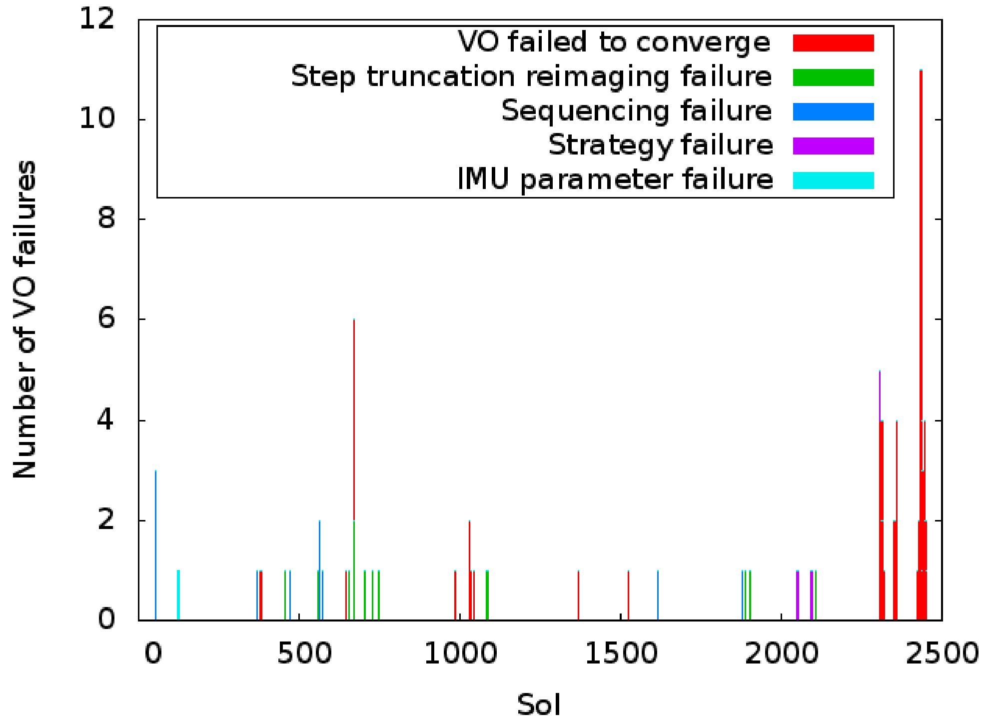

Figure 12: Number of VO failures per sol for each type of VO failure. The category that has had the most VO failures is 'VO failed to converge', which often happens on all-sandy terrain with few obvious unique features.

4 Drive Modes

Curiosity can be commanded to drive with varying amounts of autonomy and attention. At the highest level, there are three Autonomous Imaging capabilities, four path-selection modes, and two drive motor control strategies.

4.1 Autonomous Imaging

4.1.1 Visual Odometry

The process of acquiring VO images, transferring them to the CPU, downsampling them, generating a motion estimate and writing data products collectively takes 47 seconds on average, due to the overall architectural design (133 Mhz RAD750 CPU, VxWorks operating system, 512 Mbytes RAM, camera design, camera interface board design, flash memory operation). Drives are faster when VO is off, but safest when VO is fully on. So human operators choose between four operational VO modes depending on the needs of a particular plan and the current terrain.

Off No VO images are taken, no slip measurements are done.

VO Full VO processing occurs at every step, nominally 1 meter apart.

Slip Check During most of the drive no VO images are taken. But every 20 meters, a pair of stereo images is collected around a 40 cm step. That results in a slip estimate that has the potential to stop the drive if pre-established thresholds are exceeded. The distance is parameterized, but was set to 20 meters based on analysis of how deep we'd be willing to bury the wheels if we were to unexpectedly become embedded. Opportunity was stuck for five weeks after digging in after some 45 meters of commanded motion on sol 446 (Maimone et al., 2007a), and ever since then we have relied on VO as our primary means to stop us from getting embedded by measuring slip.

VO Auto In this mode, VO switches autonomously between Slip Check and Full modes, depending on local terrain conditions. There are four criteria that can cause the rover to transition to Full VO imaging: rover tilt, average motor current, angular rate during turn-in-place, and slip amount.

4.1.2 Hazard Detection

Hazard Detection generates a 3D model of the nearby terrain by processing a stereo pair of HazCam images and multiple stereo pairs of NavCam images. The 3D information is merged into a multi-layer, rover-centered 2D World Map using the GESTALT algorithm (Biesiadecki and Maimone, 2006). By default, the World Map models nearby terrain at 40x40 cm^2 resolution and has a size of 10x10 m^2. During hazard detection, the World Map is updated at the end of each drive step.

4.1.3 Visual Target Tracking

The rover can be commanded to autonomously re-center on a target as it drives. (Kim et al., 2009; Maimone et al., 2007b) describe the initial demonstration of this capability on the Mars Exploration Rovers, and Figure 14 shows some of the targets that Curiosity used to demonstrate its own VTT capability.

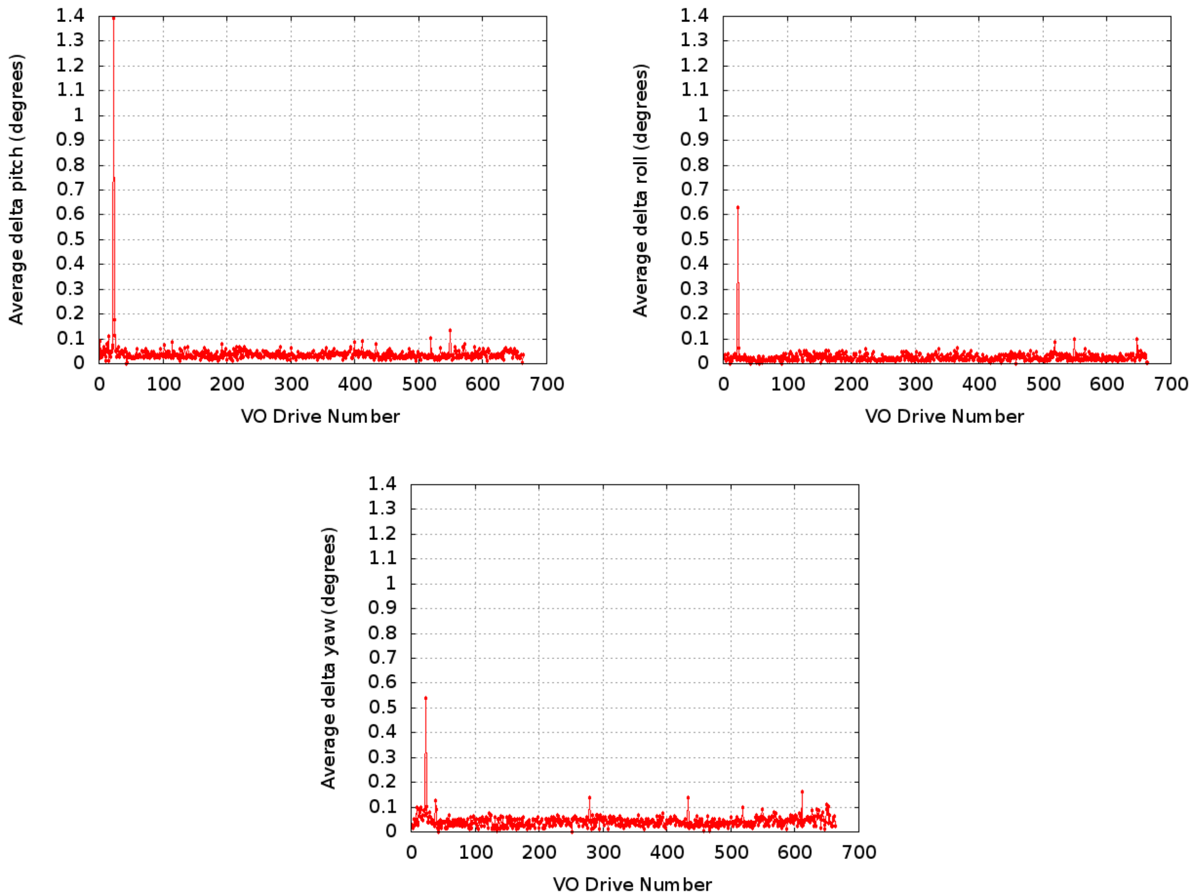

Figure 13: The average difference between IMU and VO rover attitude angles for each drive where VO was performed has been below 0.18°except for on sols 122-124. On sol 124, a bug in a IMU parameter setting was fixed.

Table 8: Key Curiosity mobility behavior camera configurations. All behaviors are reconfigurable and have changed throughout the mission, these are the most commonly used settings. Pixel resolution is specified as Rows x Columns.

Stereo Cameras	**Capture resolution**	**Processed resolution**	**Pointing Direction**	**Range (meters)**
Visual Odometry				
NavCams	256 x 1024	256 x 256	Site or Rover-fixed Frame (e.g., Forward, Right)	1.5 - 15
Autonav Forward Mapping				
NavCams	256 x 1024	256 x 256	-54° Az (Left)	2.5 - 10
NavCams	256 x 1024	256 x 256	-14° Az (Forward)	2.5 - 10
NavCams	256 x 1024	256 x 256	26° Az (Right)	2.5 - 10
Front HazCams	256 x 1024	256 x 256	Forward	0.3 - 3
Autonav Backward Mapping				
Turn in place 30 degrees				
Rear HazCams	256 x 1024	256 x 256	Backward	0.3 - 3
Rear HazCams	1024 x 1024	192 x 1024	Backward Horizon	3 - 10
Turn in place -30 degrees				
Rear HazCams	256 x 1024	256 x 256	Backward	0.3 - 3
Rear HazCams	1024 x 1024	192 x 1024	Backward Horizon	3 - 10
Visual Target Tracking				
NavCams	1024 x 1024	1024 x 1024	Site Frame Location or Azimuth/ Elevation	~ 1 - 100

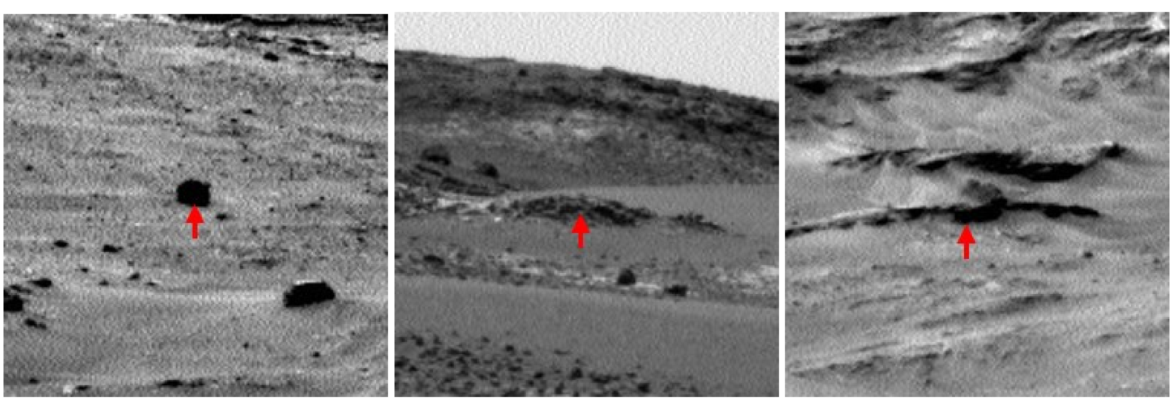

Figure 14: Examples of VTT features successfully tracked by Curiosity on sols 743, 923, and 967 for 6, 11, and 36 frames respectively. Visit `https://mars.nasa.gov/msl/multimedia/raw-images/`, select "Left Navigation Camera" and choose the sol number to see all the tracked frames.

These onboard autonomous imaging capabilities can be used simultaneously or individually, but in practice they are typically used independently. Using them together can result in significantly slower overall drive speeds, as many seconds are needed not only to perform the extra autonomous image processing, but also to re-point the NavCams between different terrain features, since such re-pointing can only occur while the vehicle is stopped. Only a single VO mode can be active at one time but the VO mode can be changed during a drive. The most commonly used ECAM configurations for Curiosity's autonomous imaging capabilities are shown in Table 8.

4.2 Path Selection

In waypoint-style driving, where the goal is specified as a point in the current Site Frame, four different path selection strategies are available. During the first seven years of the mission, 33.2% of the attempted drives have included waypoint-style driving. The remainder of the drives were planned using only arc and turn-in-place drive primitives.

Directed Drive directly toward the goal.

Guarded Drive directly toward the goal, but consult the World Map to find hazards as you go. If any cell along the path would cause the rover to enter a Keep-out Zone or get too close to a geometric hazard, the drive will terminate before planning the step that would drive onto that cell. This mode is often used for short drives across small ridge-occluded areas between visible terrains, in conjunction with collecting imagery and building up the World Map.

Avoid Keep-out Zones (AvoidKOZ) Autonomously avoid any manually-specified Keep-out Zones, but do not consider geometric hazards by consulting the World Map.

Avoid all hazards (AutoNav) Autonomously select a path to steer around any nearby geometric hazards and Keep-out Zones. Used in conjunction with collecting imagery and building up the World Map.

Only a single path selection mode can be active at one time, but the path selection mode can vary for each waypoint in a drive. If global path planning is enabled, the AvoidKOZ and AutoNav path selection modes use a version of the Field D* algorithm to choose a globally optimal path (Ferguson and Stentz, 2006), (Carsten et al., 2009). After each drive step, the World Map is merged into a Global Map having the same resolution but a default size of 50x50 m^2. Global path planning is enabled by default and has been used for all portions of drives during the mission where the AvoidKOZ or AutoNav path modes were selected. Planning is done in the 2.5-D world model without predicting future slip (Biesiadecki and Maimone, 2006).

4.3 Drive Wheel Speed Control

Curiosity implements arc-based driving using traditional double Ackermann steering control, pointing each corner wheel independently along a tangent to the turning circle for that wheel's radius.

Two options exist for controlling each wheel's speed:

Constant Speed When driving in its default mode, the FSW commands each wheel to rotate using a constant angular rate. The maximum rate is 0.168 radians/s, which translates into a maximum linear wheel speed of 4.2 cm/s. Wheels with the greatest turning radius are commanded at this highest speed, with other wheels' rates set in proportion, so that all wheels will end the drive segment at the same predicted time.

Terrain-adaptive wheel speed control Since sol 1678, we have primarily used a new terrain-adaptive wheel speed control algorithm called TRCTL (Toupet et al., 2020). The TRCTL algorithm combines real-time suspension and attitude angle measurements with a rigid-body kinematic model to generate real-time estimates of idealized (no slip) wheel speeds. In this mode, at least one wheel is commanded at the maximum wheel angular rate, while the other rates are scaled accordingly. Wheels climbing rocks are sped up due to the resulting change in suspension and attitude angles, as they must cover more distance than those on flat ground. TRCTL was implemented as a hot patch to the flight software and it commands the speed of each wheel at 8 Hz.

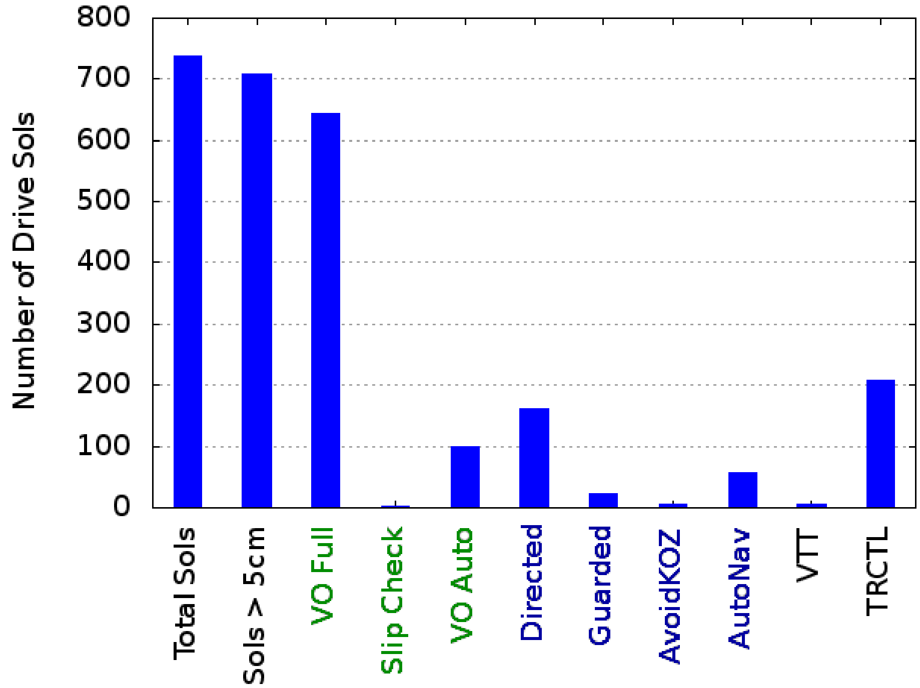

Figure 15: Number of sols using each drive mode. The VO modes have green labels and the path selection modes have blue labels. The sum of the usage of drive modes is more than the number of drive sols because multiple drive modes can be used in a single drive. The odometry on 29 drive sols was under 5 cm. The purpose of drives that short is typically to better position the rover with respect to a selected target for robotic arm activities.

5 Drive Odometry, Rate, and Frequency

Use of the various drive modes has changed as the mission has progressed. Figure 15 shows the number of drive sols that employed each drive mode, Figure 16 shows the commanded odometry for each drive sol, categorized by drive mode, and Figure 17 shows the cumulative commanded odometry for each drive sol, categorized by drive mode. Although a single VO mode and path selection mode can be active at one time, multiple modes can be used in a single drive. For example, VO Full and Directed could be used to drive to the first waypoint, and VO Auto, AutoNav, and TRCTL could be used to drive to the second waypoint. For Figures 15 - 17, commanded odometry for each drive command is assigned to a single drive mode. For drive commands with VTT enabled, the odometry for that command is categorized as VTT odometry, regardless of the VO mode and path selection mode. For drive commands with VTT disabled and a path selection mode selected, the odometry for that command is categorized by the selected path selection mode, regardless of which VO mode is selected.

Figure 18 shows a comparison of Curiosity and Opportunity actual odometry. Although the comparison is of historic interest, mobility choices are guided by each mission's long term strategic science plan, and are subject to changes due to near term science objectives and engineering safety constraints arising from terrain features not evident from orbital planning images. Other factors that affect drive frequency are times when a rover is stationary for extended periods, such as during drill campaigns, transition to a new flight software version, anomaly investigation and recovery, and solar conjunction (when Mars is behind the Sun relative to Earth, resulting in limited communication).

Referring to Figure 17, the rover drove relatively little during the first year, mainly because we had the good fortune to land in an area rich with targets of interest to the science team ("Yellowknife Bay"). It did not take long to reach them, so we mainly exercised directed driving with occasional VO for the first 200 sols. After the first year we started driving as fast and far as possible, making use of VO Auto for slip safety and AutoNav to enable the rover to extend human-planned drives safely into terrain unseen by human eyes. This is evident in the increasing slope in Figure 17 and the distance-per-sol records in Figure 16. Discovery of wheel skin damage around sol 490 and our first partial embedding event on sol 672 (see Figure 19) each led to downturns in drive rate during the subsequent weeks. Those events and the discovery around sol 710 (in "Hidden Valley") that the rover's performance in polygonally-rippled sand was insufficient to make good progress led us to favor somewhat slower VO Full drives ever since, given that mode can react most quickly to any unexpected slip events (Arvidson et al., 2017b).

Over 88% of Curiosity's driving has been accomplished using some form of VO autonomous software, demonstrating the operations teams' choice to reap the benefits of onboard autonomy; even though it resulted in slower drive progress, driving overall was safer and more effective due to reduced positional uncertainty.

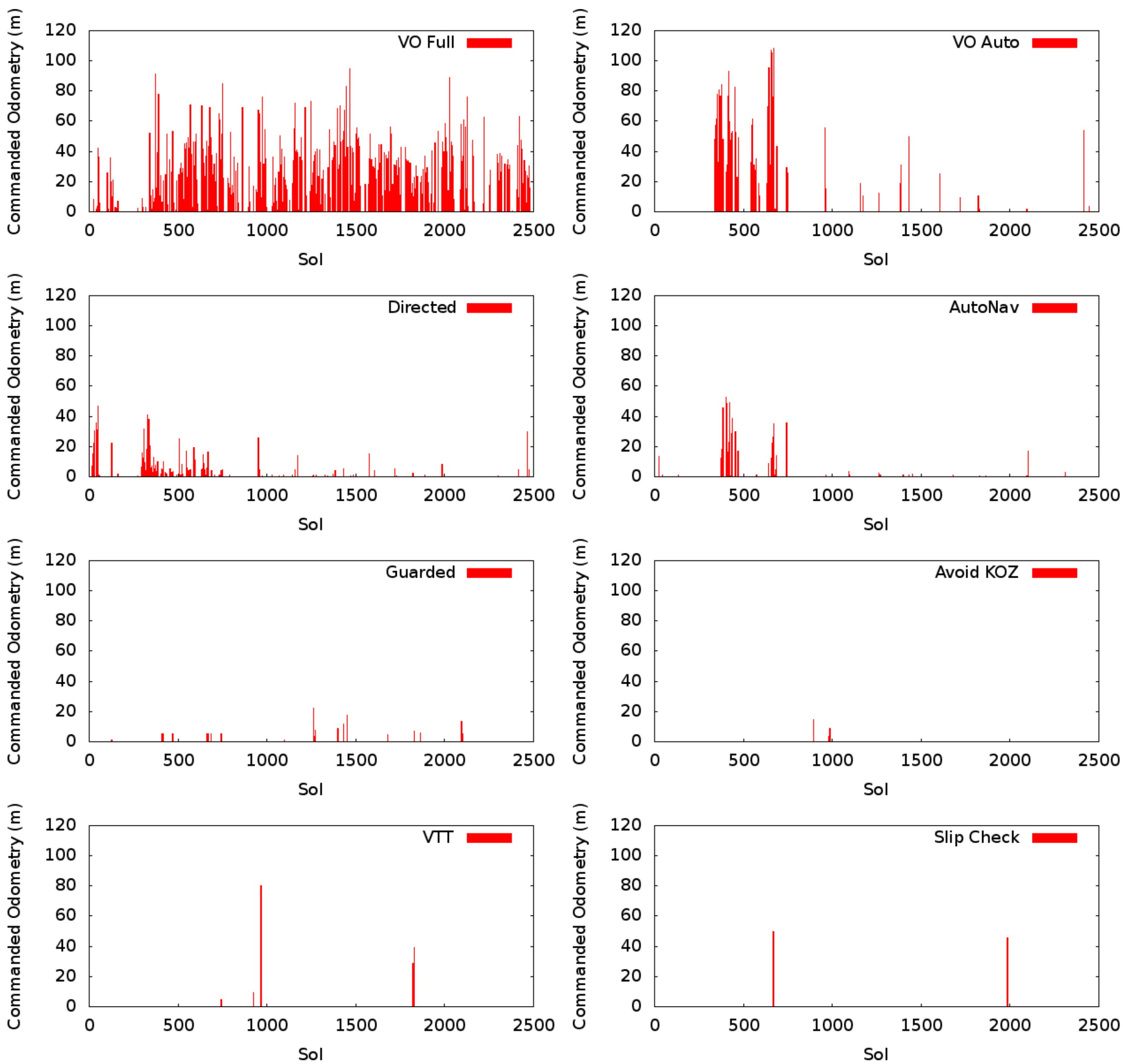

Figure 16: Curiosity commanded odometry in each drive mode per sol. Multiple drive modes can be used in a single drive. Drive commands with VTT enabled are categorized as VTT odometry, drive commands with VTT disabled and a path selection mode selected are categorized as odometry for the selected path selection mode, and remaining drive commands with a VO mode selected are categorized as odometry for the selected VO mode. VO Full is the most often-used drive mode. The least used drive modes are AvoidKOZ (commanded on sols 896, 978, 986, and 987), Slip Check (commanded on sols 665, 668, and 1986), and VTT (commanded on sols 743, 923, 967, 1822, and 1829).

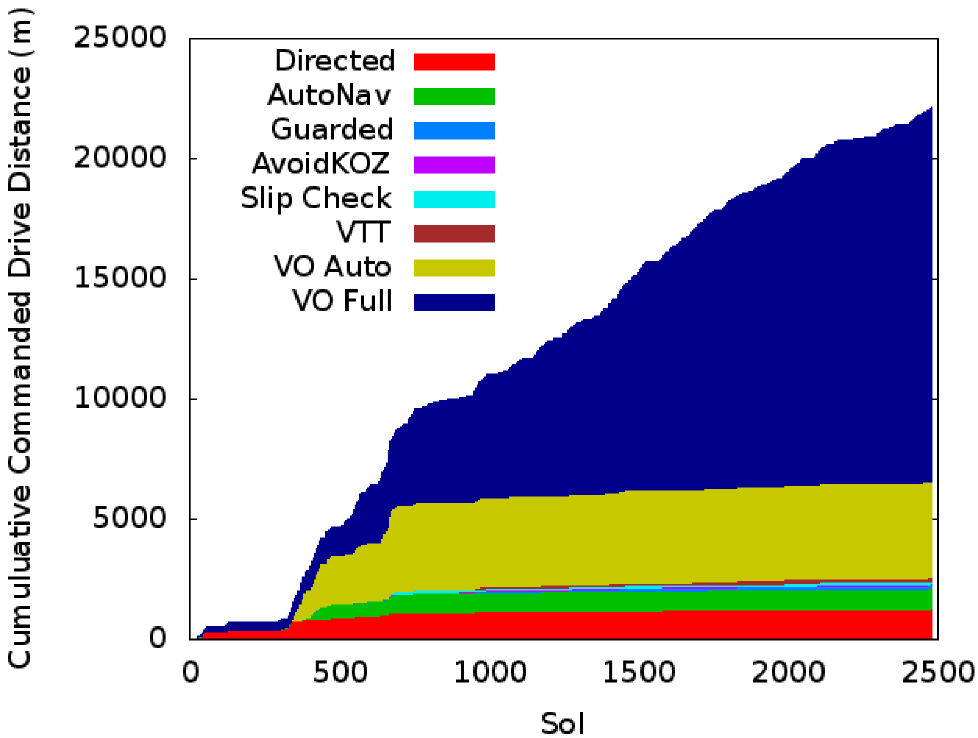

Figure 17: Curiosity cumulative commanded odometry by drive mode. Multiple drive modes can be used in a single drive. The most often-used drive modes are VO Full, VO Auto, Directed, and AutoNav.

Figures 20 and 21 illustrate the different drive rates possible for various combinations of vision-based autonomy with TRCTL disabled and enabled, respectively. Recall that since TRCTL entails only one wheel guaranteed to be traveling at the max wheel speed, one might expect longer drive times for achieving the same drive distance. Indeed, this can be seen in the empirical effective traverse rates with TRCTL enabled and can be viewed as a performance tradeoff made in favor of preserving wheel health.

At the end of every drive, performance statistics are extracted from telemetry and reported to the operations team. The best such odometry statistic, and the one closest to ground truth we have available, is the ideal path length scaled according to VO corrections, as it incorporates the ideal vehicle kinematics as well as any deviations from it as observed in VO updates.

There have been 738 attempted drives as of sol 2488, resulting in a cumulative odometry of 21,318.545 meters. Curiosity's drive distances each sol have ranged from its shortest drive of 2.6 centimeters (sol 1555) to its longest drive of 142.5 meters (sol 665, see Figure 22). The odometry for 29 of the 738 attempted drives (3.9%) was less than 5 cm. The purpose of very short drives is typically to reposition Curiosity in preparation for robotic arm activities on a selected science target. The average odometry per attempted drive is 28.9 meters, and the average drive frequency is once every 3.37 sols.

The amount of distance commanded is generally determined by the near term science goals. For much of the mission, the focus has been on using the arm to perform *in situ* measurements on or close to the Martian surface. As such, there is often a goal to "drive to this nearby target", or "do not change elevation more than this amount before stopping". Such operational constraints limit how long a given sol's drive will be. It is only when there is a desire to pass by much of the local terrain that long-distance drives are desired, and planned. We have not attempted to characterize each sol's science team goals in setting drive distances for this paper.

Curiosity has two general purpose RAD750 computers, one of which functions as the primary and the other as a backup. These are referred to as Rover Compute Element A (RCE-A) and Rover Compute Element B (RCE-B). At the

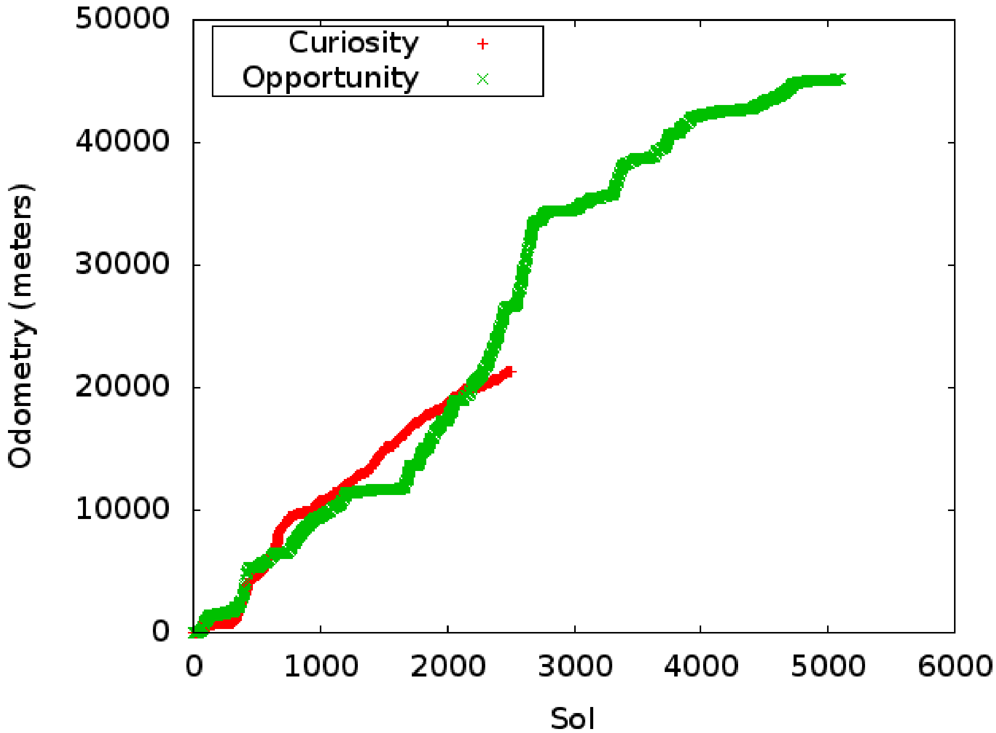

Figure 18: Curiosity and Opportunity cumulative actual odometry. Although of historic interest, drive decisions are guided by each mission's long-term strategic science plan, near-term science objectives, and terrain-dependent engineering safety constraints.

start of the mission, RCE-A was the prime computer and RCE-B was the backup computer. Due to an anomaly related to a failing region of RCE-A NAND flash memory, the operations team commanded a swap to RCE-B on sol 201. After the data product partition on RCE-B failed to mount on sol 2173, the operations team switched back to RCE-A on sol 2188 until after the RCE-B data product partition was reformatted on sol 2342. The cumulative odometry performed on RCE-A and RCE-B are 1,158.793 meters (5.63%) and 20,159.565 meters (94.37%), respectively, with RCE-A mobility having occurred between sols 15-166 and sols 2250-2338.

6 Drive Direction

Rover driving can be performed in the forward direction, in the backward direction, or by turning in place. Turning in place is commonly used on benign terrain 1) after the rover reaches a waypoint, to align itself with the next waypoint, or 2) after the rover has reached the drive goal position, to turn to a heading optimal for transmitting telemetry to a Mars orbiter or directly to Earth. Turning in place does not use TRCTL, regardless of whether it is disabled or enabled in software parameters. Steering on harsh terrain can cause more wheel damage than driving on harsh terrain. Since turning in place requires steering the outer four wheels, turning in place is typically planned on mostly benign terrain.

Although backwards driving has been shown to reduce the forces on the middle and front wheels, forward driving is much more common than backward driving for two primary reasons related to the desire to limit turning in place. First, transitioning between a forward drive and a backward drive in the most efficient manner typically requires turning in place. Secondly, a turn-in-place is typically needed at the end of a backward drive to perform post-drive imaging in the direction of the next drive. This is because the rover body occludes nearby terrain when imaging backwards with the ECAMs on the mast. Post-drive imaging is performed to update the ground-based terrain mesh used to plan the next drive.

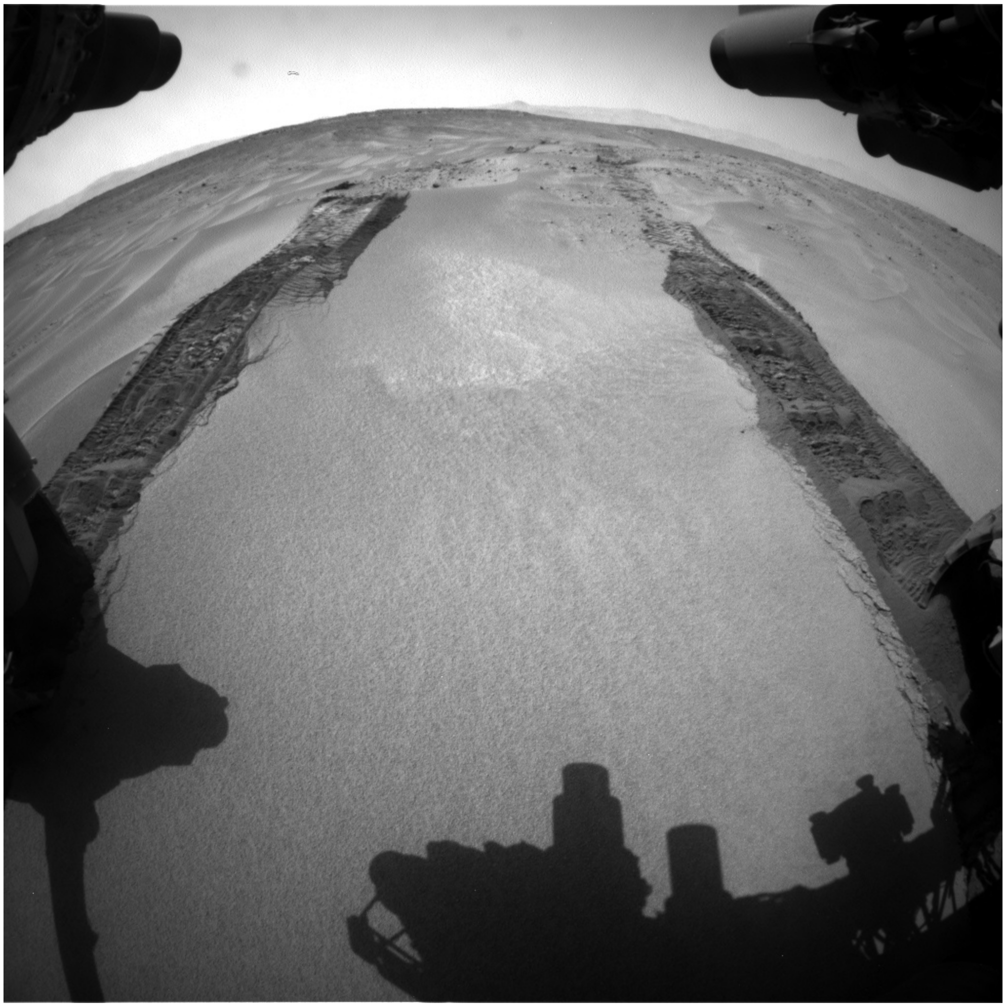

Figure 19: Front hazcam view of the sol 672 partial embedding event where VO Auto stopped the backwards drive early.

Backwards driving can add up to 360°of turning in place to a drive; up to 180°at the beginning of the drive to transition from the imaging position of the previous drive to the rear of the rover pointed in the direction of the first waypoint, and up to 180°at the end of the drive to acquire post drive images in the direction of the next drive. A turn in place of 360°results in 10, 7.44, and 9.5 meters of additional wheel odometry for the front, middle, and rear wheels, respectively. During that additional wheel odometry, additional wheel damage can occur. In addition, allocating time for backwards driving related turning in place reduces the translational distance that can be achieved in the allowable drive time.

Figure 23 shows the cumulative commanded forward and backward odometry up through sol 2488. The cumulative commanded forward and backward odometry are 17,805.671 meters (80.1%) and 4,435.860 meters (19.9%), respectively. On sol 546, backwards driving usage sharply increased in response to wheel wear test results from the JPL Mars Yard indicating forces on wheels are lower for backward driving than forward driving. However, there was no change in Curiosity's wheel damage rate due to the additional wheel odometry from turning in place. On sol 671, backwards driving usage was sharply decreased, given it did not decrease Curiosity's wheel damage rate but reduced the overall drive distance achievable in the allocated time.

Positive wheel angular rates for a left and right wheel corresponds to forward driving, negative wheel angular rates for a left and right wheel corresponds to backward driving, and left and right wheel angular rates with a different sign corresponds to turning in place. Angular rate data for the LF and RR wheels were analyzed up through sol 2488. The

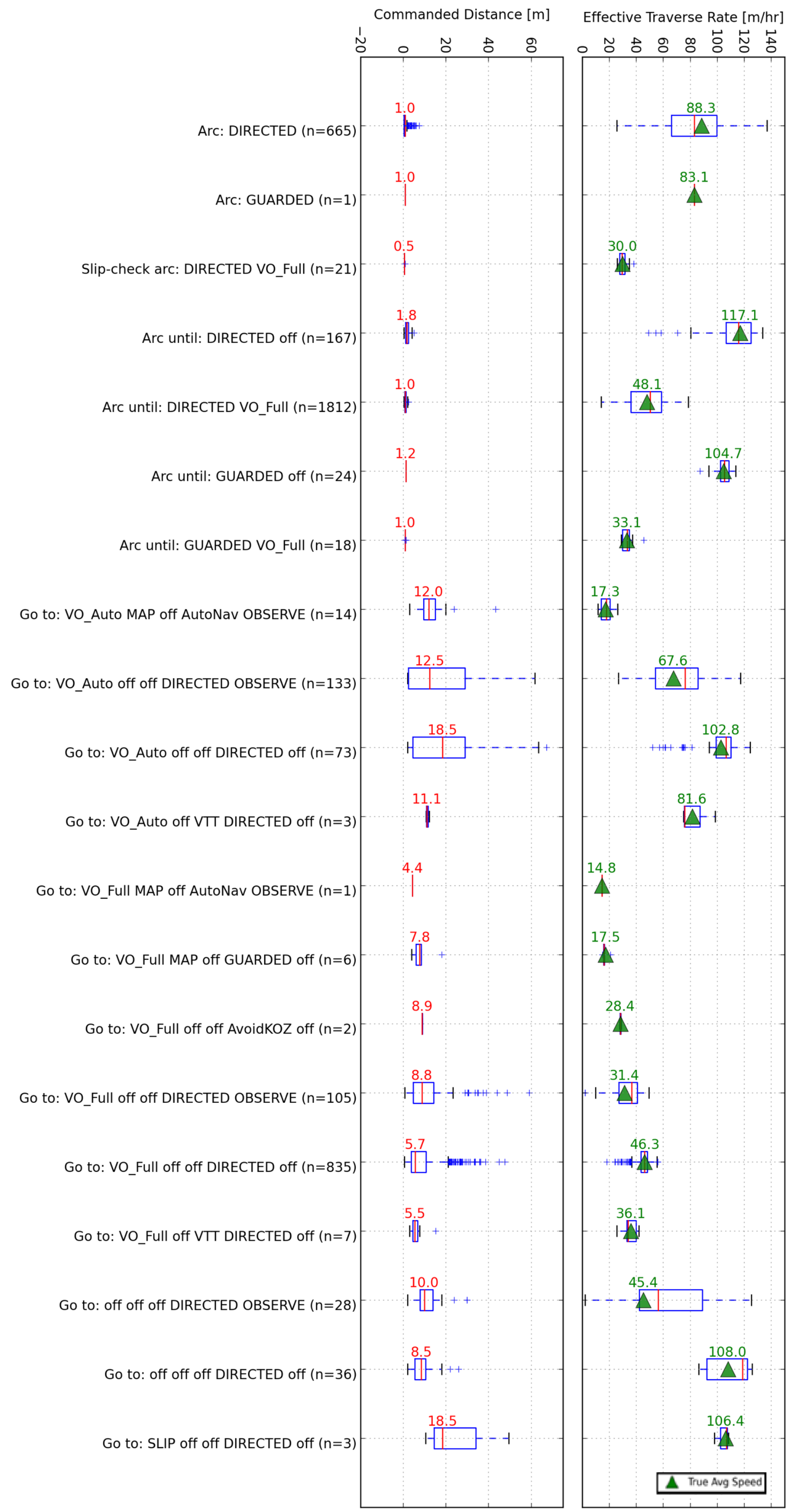

Figure 20: Effective drive rates without TRCTL. Boxplot showing interquartile range (blue) and median (red) for traverse rate and duration of each drive command by mode. Rather than reporting the "mean of the achieved speeds," which is not a meaningful quantity, we instead indicate the true average speed (quotient of total drive distance and total drive duration) for each mode with a green triangle and numeric label. The order of the arguments for "Go to" are VO mode, whether or not to update the Hazard Detection map, whether or not to perform VTT, path selection mode, and whether or not to run an observation sequence to acquire mid-drive images.

Figure 21: Effective drive rates with TRCTL enabled.

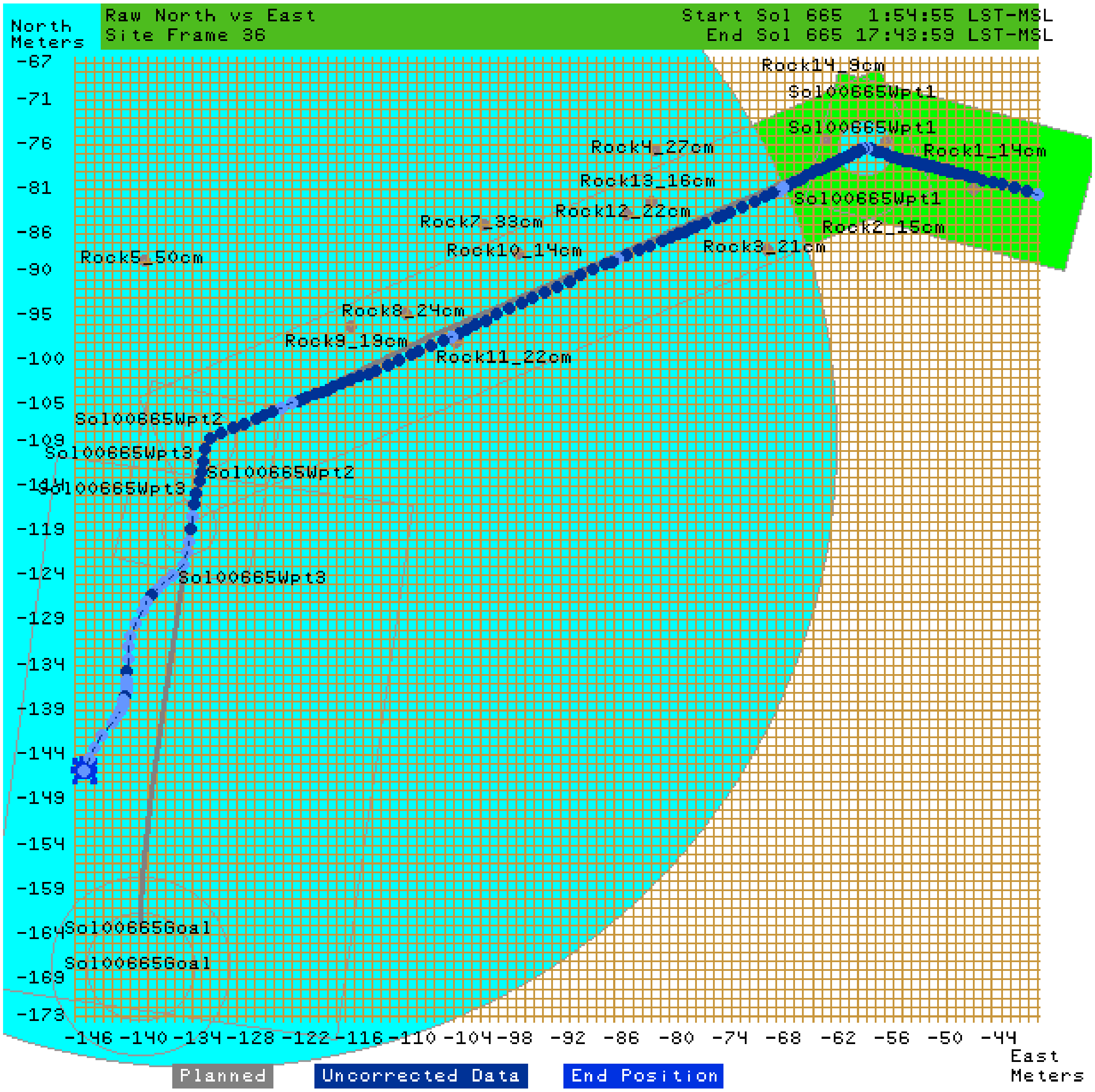

Figure 22: Course plot of the longest single-sol drive (sol 665, 142.5 meters) auto-generated by ground tools for mobility performance assessment. The drive started in the upper right and ended on the way to the goal at the bottom left. The grey path was the simulated path, the blue dots indicate the route actually taken. Dark blue dots indicate drive steps without images, light blue dots indicate steps with VO and/or Hazard Detection images, grey dots indicate terrain features individually labelled by RPs. Grey rectangles indicate keep-in zones and gray circles indicate waypoints (including commanded tolerances). The final 25 meters of the drive were in AutoNav mode, and the drive terminated successfully when the specified time limit for the drive was reached.

number of executed forward, backward, and turn-in-place moves are 4,835,049, 1,224,897, and 594,170, respectively. The percentage of the moves that were forward, backward, and turn-in-place are 72.7%, 18.4%, and 8.9% respectively. The average rover pitch during forward, backward, and turn-in-place moves has been 3.5, 2.3, and 2.9°, respectively.

7 Fault Protection

Drives can stop earlier than expected for a variety of reasons; one example is when Curiosity detects wheel slippage exceeding the limits set for that drive. The rover's flight software monitors dozens of states and thresholds, any of which might lead to the raising of a mobility fault. There are two kinds of mobility faults: a *Goal Error* alone simply means that a command was unable to reach its desired goal state but the rover is still safe, while a *Motion Error* means some safety threshold was exceeded and therefore the operations team must assess the circumstances and correct it. Once either fault has been raised, future mobility commands will recognize that status and gracefully fail without even attempting to move the rover. In this section, we review drives that failed to accomplish all their planned motions, and explain the circumstances that led to their early termination.

7.1 Planned drives that were not attempted

Curiosity drives were planned by the MSL operations team on 754 sols. However, drives planned for 16 of the sols were not even attempted by Curiosity for these reasons:

Safe mode When an anomaly occurs, Curiosity stops executing the current plan and causes the prime RCE to reboot into safe mode. The three sols Curiosity did not attempt a planned drive because the rover was in safe mode are 697, 1391, and 2340. For example, the drive planned for sol 1391 was not attempted because flight software detected an inconsistency on sol 1389, which caused the prime RCE to reboot into safe mode.

Deep space network (DSN) transmission issue The seven sols Curiosity did not attempt a planned drive because the plan was not received by Curiosity are 596, 599, 1070, 1165, 1308, 1855, and 1952. For example, the drive

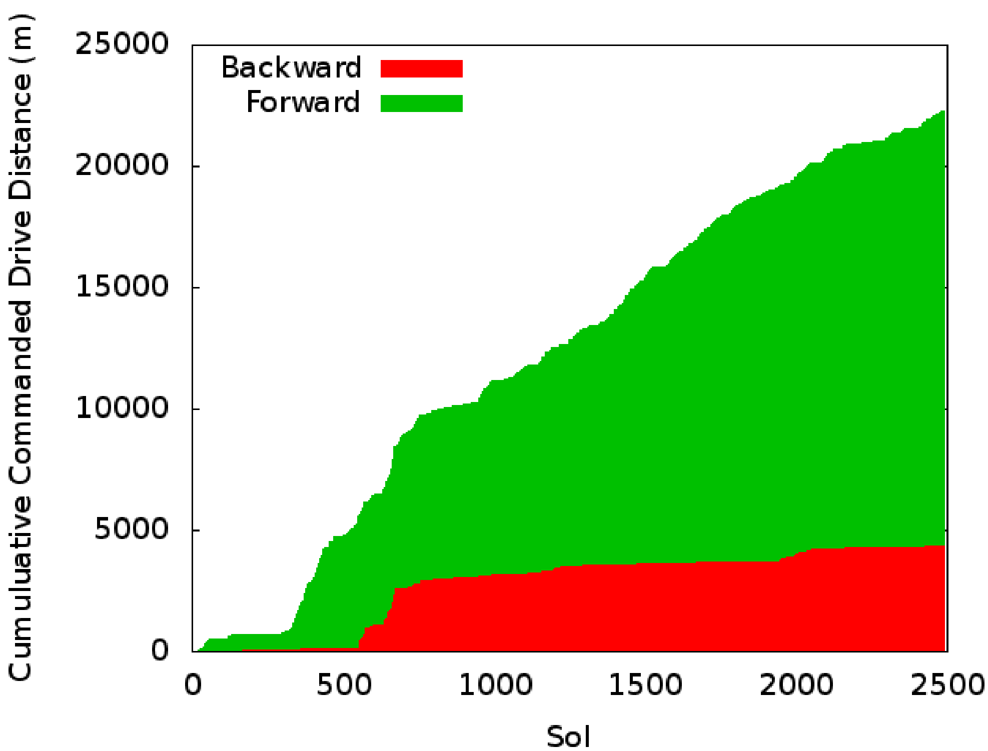

Figure 23: Curiosity cumulative commanded odometry by drive direction. Backwards driving was increased on sol 546 in response to observed wheel damage, but was reduced on sol 671 because it did not reduce the wheel damage rate but reduced the overall drive distance achievable in the allocated time.

planned for sol 1070 was not attempted because there was a complex-wide power outage at the Madrid DSN site that prevented transmission of the plans for sols 1068-1070.

Planned drive withdrawn before uplink The six sols Curiosity did not attempt a planned drive because the plan was withdrawn before uplink are 104, 912, 933, 1312, 1823, and 2046. For example, the planned drive for sol 933 was withdrawn after a downlink revealed some of the sol 931 robotic arm activities failed due to a missing file.

Figure 24 shows the temporal distribution of the 16 planned drives that were not attempted by Curiosity. The cumulative predicted odometry for those 16 planned drives was 377.9 meters. On subsequent sols, 11 of the unattempted drives were replanned with no or little change, and 5 were replanned with significant change to the route or distance.

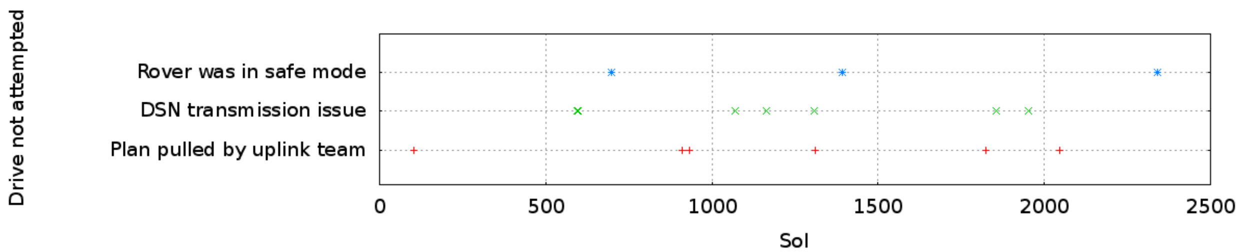

Figure 24: Sixteen drives were planned but not attempted by the rover.

7.2 Planned drives that were attempted

Of the 738 drives that were attempted, 622 (84.3%) successfully completed with the rover reaching its goal position, while 116 drives (15.7%) did not run to completion. Despite 116 drive faults occurring, 91.7% of the predicted cumulative odometry over the 738 attempted drives was achieved. Of the 116 drive failures, 29 of them were expected and 87 were unexpected. Figure 25 lists the 24 reasons why the 116 drive failures occurred, and includes the number of expected and unexpected drive faults for each reason. A drive fault is categorized as expected if a RP predicted in their daily plan summary that a drive might end early for a specific reason, and it did.

26 of the 29 expected drive faults were due to exceeding the time-of-day (TOD) limit, a specific time when a drive sequence must stop (if it is still running) so there is time to run the other activities included in the plan. An example of this is stopping the drive at a specified time to be able to acquire post-drive imaging (for planning the next drive) before transmitting data to a Mars orbiter at a scheduled time. Autonomous hazard-avoiding drives are another common case, since they rely on the TOD limit to end the drive so that the rover can drive as far as possible in the allotted time. The other cases of expected drive faults include one occurrence each of exceeding the slip limit (sol 983), exceeding the tilt limit (sol 151), and entering a keep out zone (sol 163).

Referencing Figure 25, 16 of the 24 drives that faulted did so due to mobility events. The other 8 non-mobility reasons why drives faulted are 1) exceeding the TOD limit, 2) the robotic arm was not stowed, 3) a Multi-Mission Radioisotope Thermoelectric Generator (MMRTG) short was detected, 4) a Mast Camera (MastCam) focus mechanism was not stowed, 5) the Sample Analysis at Mars (SAM) instrument was not safe for driving, 6) the Chemistry and Mineralogy (CHMN) instrument was in use, 7) a RSM error occurred, and 8) a limit on the difference between a VO and rover IMU attitude angle was exceeded.

Responses to non-mobility faults vary, and can change over the lifetime of the mission. Exceeding the TOD limit and exceeding the limit on the difference between a VO and IMU attitude angle both stop a drive that is in progress. However, the other 6 non-mobility drive faults will prevent a drive from ever starting. The response to a fault can also be changed by updating a parameter. For example, there have been 5 occurrences of a MMRTG short preventing a drive from starting, the last occurring on sol 1305. On sol 1309, the operations team changed a short response

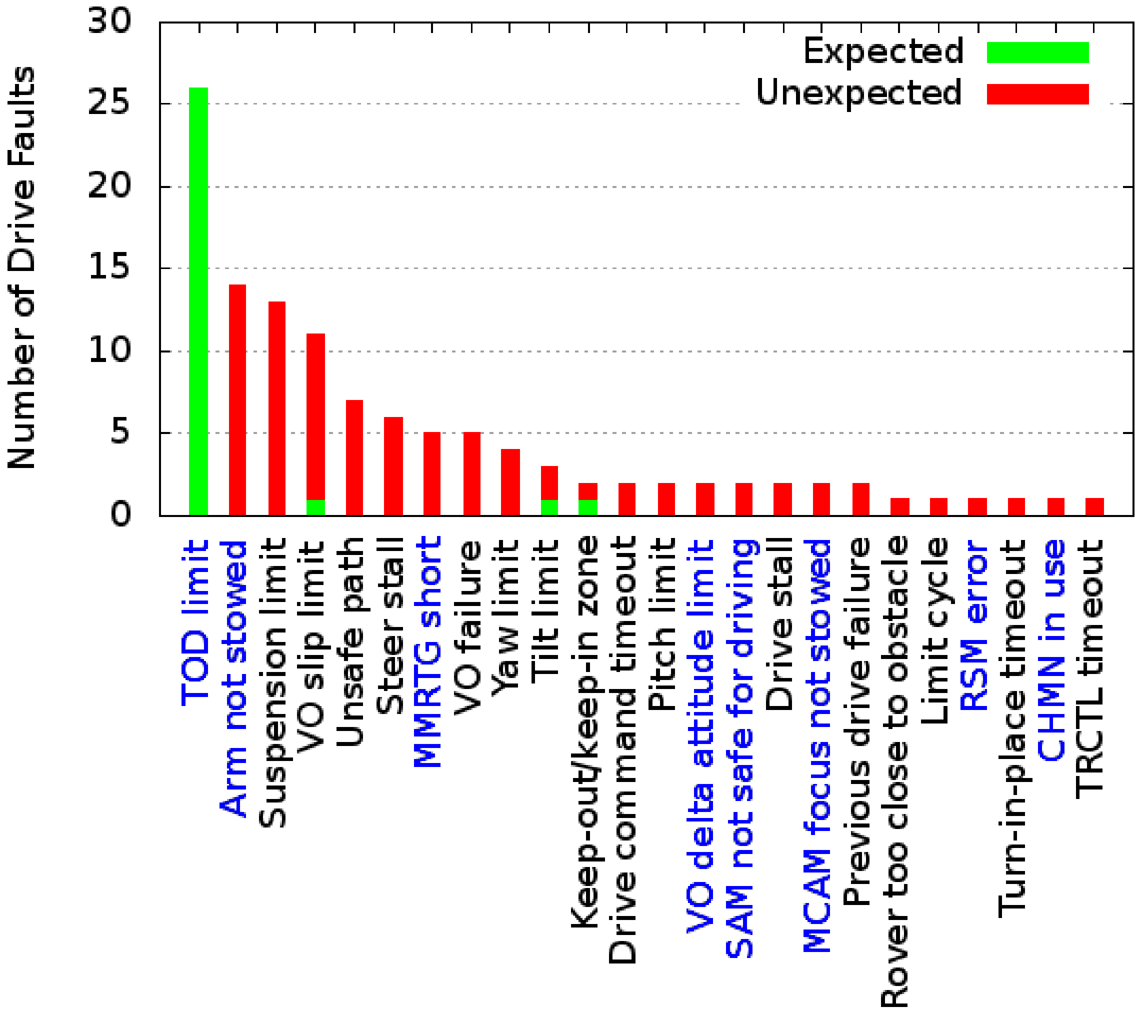

Figure 25: Number of expected and unexpected drive faults for the 24 categories of fault protection that have caused incomplete drives. The categories are ordered from most numerous (left) to least numerous (right). Eight of the categories are from general fault protection (blue) and sixteen are from mobility fault protection (black).

parameter to "ignore" for all steer and drive actuators, so that subsequent occurrences of the MMRTG short no longer prevented a drive. Figure 26 illustrates the temporal distribution of all the drive faults.

When the RPs simulate a planned drive using a ground tool called Robot Sequencing and Visualization Program (RSVP), the predicted odometry of the drive is generated. After the drive is executed, the actual odometry is recorded in the downlink telemetry. Figure 27 illustrates the difference between the predicted and actual odometry for the 738 attempted drives. For most of the drives, the difference between the predicted and actual odometry is close to zero. The difference is large where a drive faulted at the beginning of a drive or mid-drive. The difference is negative where the rover drove further than predicted. This can happen when a portion of a drive is executed with AutoNav. For example, on sol 385, Curiosity drove 141.5 meters, 5 meters further than predicted due to AutoNav avoiding hazardous terrrain near the end of the drive.

The error states from drive faults prevent further driving until they are cleared. A TOD-limit drive fault sets a mobility goal error that is automatically cleared so that planned post-drive turns to a rover heading ideal for communications and/or wheel straightening occurs. On sol 151, after tripping an expected tilt-limit drive fault, the mobility motion and goal errors were automatically cleared and the arm was unstowed. The error states from other drive faults, however, required ground-in-the loop to clear the error states before the next drive. Figure 28 shows the number of sols that

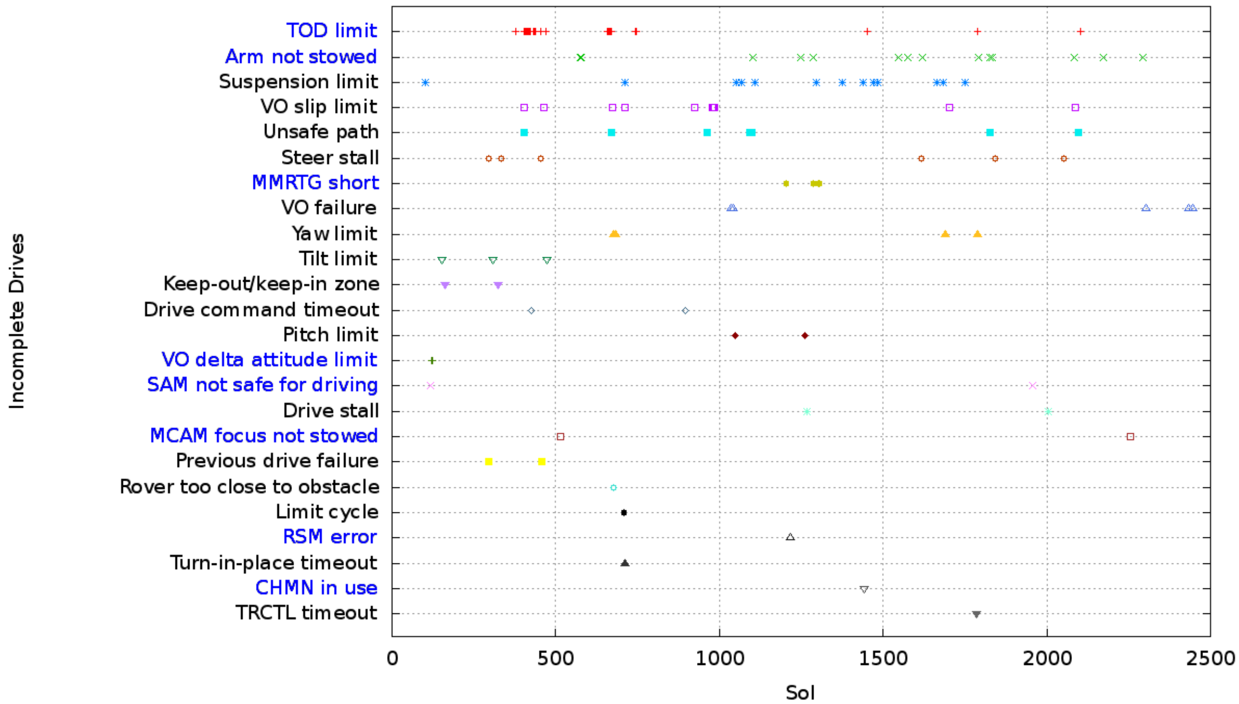

Figure 26: Temporal distribution of all the drive faults for the 24 categories of fault protection that have caused incomplete drives. The categories are ordered from most numerous (top) to least numerous (bottom). Eight of the categories are from general fault protection (blue) and sixteen are from mobility fault protection (black).

elapsed before the operations team cleared the mobility error states to enable the next drive. Where there was a TOD-limit drive fault, the number of sols is zero since the error state is cleared automatically. For other drive faults, mobility error states are cleared in the next drive sequence.

The four mobility error states are 1) mobility goal error (the drive faulted short of the goal position), 2) mobility motion error (mobility fault protection faulted the drive during motion), 3) mobility is precluded (the drive faulted because a previous sequence conditional precluded mobility), and 3) DO_MOBILITY is false (the drive faulted because there was an onboard detected condition that prevented the drive from starting). Because a mobility motion error causes a drive to stop short of the goal position, it trips a mobility goal error. An example scenario where a sequence can preclude mobility is when there is a two sol plan with arm activities during sol N and mobility activities during sol N+1. If the arm sequence fails to stow the robotic arm, it will preclude mobility so that the sol N+1 drive faults before it starts. The conditions that cause DO_MOBILITY to be false are a mobility goal error, a mobility motion error, mobility is precluded, the arm is not stowed, the MAHLI lens cover is not closed, a MastCam focus mechanism is not stowed, the CHMN or SAM instrument is in use, or the Chemistry & Camera (ChemCam) instrument is not currently in a Sun-tolerant focus range.

81.0% of mobility fault states are cleared within a sol or two. Drive faults occuring on sols where tactical planning is not scheduled (e.g., on a weekend) can lengthen the period before clearing mobility error states. The longest period before clearing mobility error states is 12 sols, occurring after the sol 2173 anomaly due to an investigation to identify the root cause. Long periods before clearing mobility error states can be due to a change in near-term science plans or the proximity to a project stand-down period (e.g., solar conjunction or holidays). After the sol 455 RF steer stall, the project decided to perform proximity science with the robotic arm before continuing driving; the mobility goal error was cleared 10 sols later. After the sol 102 suspension drive fault, the drive planned for sol 104 was withdrawn late in process due to a concern that the planned final rover attitude would be less-than-ideal for downlinking telemetry. Further driving was delayed until after the approaching Thanksgiving holiday. The mobility motion and goal errors were cleared 9 sols after the drive fault.

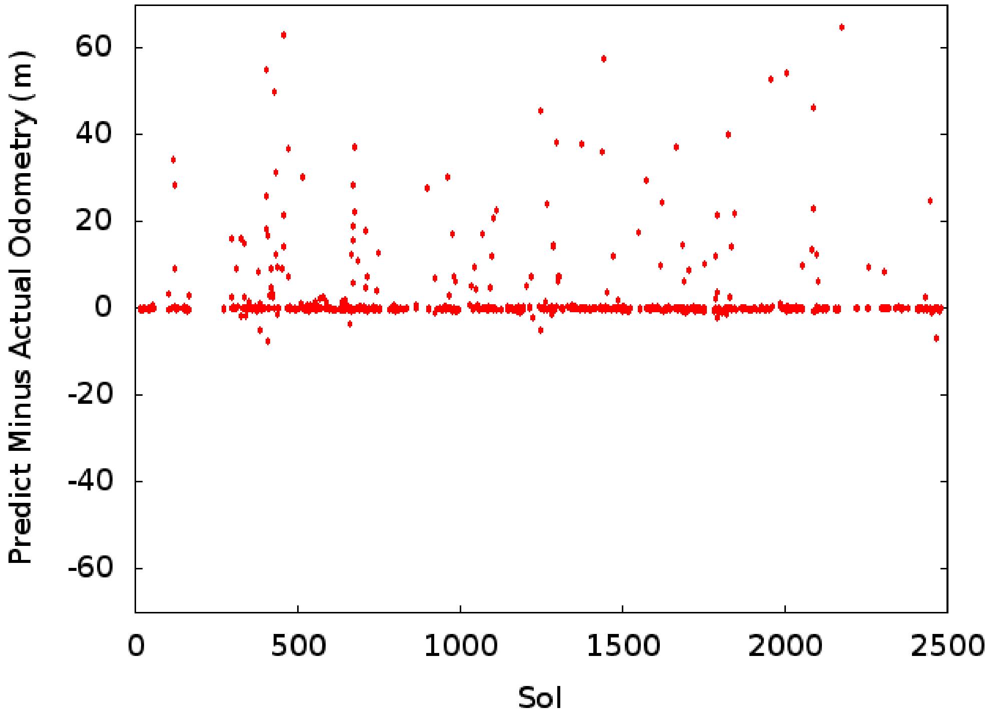

Figure 27: Difference between the predicted and actual odometry for each drive sol. For most drives, the difference is close to zero.

7.3 Planned drives that failed due to mobility fault protection

Real-time human intervention during drives on Mars is not possible due to the latency in uplinking commands and downlinking telemetry. Therefore, the flight software was designed to safeguard the rover during all activities, including driving. During a drive, mobility fault protection evaluates rover state at 8 Hz. If any state relevant to driving is outside of set limits, a drive fault will occur, stopping the drive. Of the 116 drive faults that have occurred, 63 have been due to 16 types of mobility fault protection.

The operations team has the discretion to alter mobility fault protection limits to match the expectations for the drive. For example, if the drive simulation over a 3D terrain mesh shows a suspension angle will exceed its default conservative setting, RPs will increase the suspension angle limit to be slightly above the maximum simulated suspension angle. Many such limits are nominally set somewhat conservatively, and only increased when the traverse simulation shows that more complex terrain is expected to be encountered.

7.3.1 Geometric Hazard Faults

Unsafe path

During autonomous hazard-avoiding drives, the terrain is analyzed at each drive step and a safe step that brings the rover closer to its goal is selected. But if the path evaluations of all available arcs for a drive step fail to meet the safety threshold, an unsafe path fault is declared and the drive is stopped. During a guarded drive, only the most goal-directed forward or backward arc is considered and evaluated for safety. A common use case of guarded drives is when the desired path would need to cross a small patch of unknown data in the terrain mesh, and the operations team prefers to restrict the rover from autonomously discovering a new path (e.g., due to wheel wear concerns). The team will

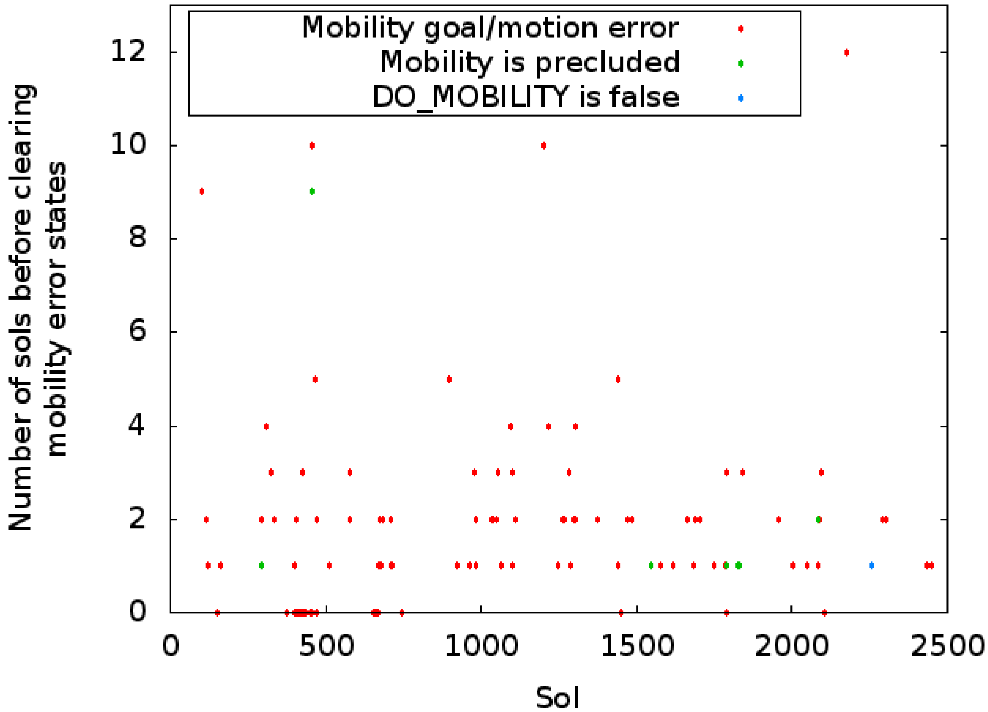

Figure 28: Number of sols after each drive fault the mobility error states were cleared, enabling additional driving. The mobility error states that prevent driving are a mobility goal error, a mobility motion error, mobility is precluded, or DO_MOBILITY is set to false.

position the rover a few meters short of the unknown region, then let the rover evaluate the terrain; as long as it is determined by the rover to be safe, the drive will continue. An unsafe path has caused 7 drive faults, 5 during guarded driving (sols 963, 1094, 1098, 1828, and 2095) and 2 during AutoNav driving (sols 404 and 671). Figure 29 contains the final auto-generated terrain World Map from sol 1828 where an unsafe path drive fault stopped the drive 5.7 cm short of the navigation goal.

Rover too close to an obstacle

During Guarded and AutoNav drives, the rover uses its onboard World Map to determine whether it is safe to drive. When building the Guarded or AutoNav portion of a drive sequence, the RPs verify the first few meters of terrain in the drive direction is safe for driving via visual inspection of downlinked images. The drive sequence first primes the World Map by processing ECAM images of terrain in front and/or behind the rover (establishing the safety of the terrain that will be under the rover when beginning the drive on actually-unknown terrain), then driving 2.5 meters onto that initial World Map data so that the 3D shape of the terrain under the wheels is known. Next, the drive sequence commands the Guarded or AutoNav drive, which continually processes ECAM images and updates the World Map. If an obstacle is too close to the rover in the World Map in the drive direction, and antigoalward driving is disabled, a NO_PATH drive fault will occur preventing further driving.

The rover being too close to an obstacle has caused one drive fault on sol 677. After commanding 16.5 meters of Directed driving up to a ridge, Curiosity transitioned to AutoNav driving. After generating a World Map, Curiosity executed a 2.5 meter Directed drive onto the map and updated it. As illustrated in Figure 30, GESTALT determined the ridge in front of Curiosity to be untraversable due to its conservative parameter settings (in response to the wheel wear concerns at that time, a 20 cm elevation difference found anywhere within a 2.6 meter inscribed disc would result in a red "untraversable" assessment in the map). To avoid the hazard, AutoNav commanded a sharp 0.5 meter arc to the left with a heading change of -28.6°. The right-most image in Figure 30 shows the proximity of the front wheels

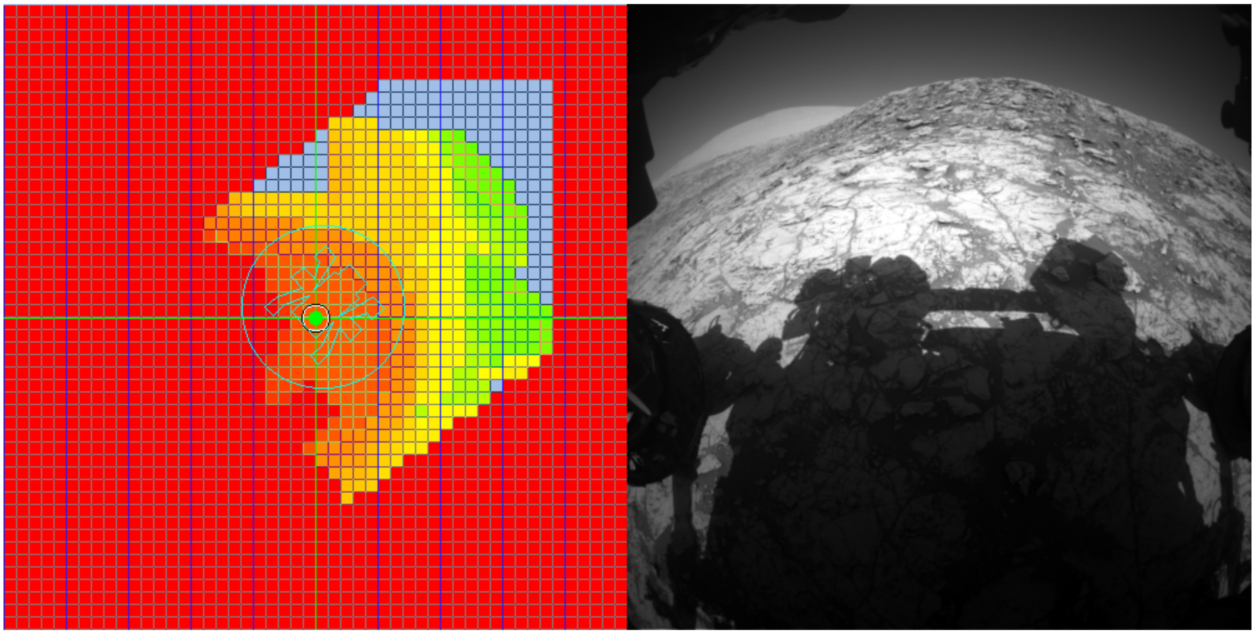

Figure 29: Final rover-centered, auto-generated terrain World Map (left) and front left HazCam image (right) from the sol 1828 guarded drive that faulted with an unsafe path due to the higher terrain tilt ahead of the rover. Curiosity was driving in the direction of the bottom left corner of the map. The map size is 10x10 m^2 and the resolution of each map cell is 40x40 cm^2. The red map cells correspond to hazardous terrain or terrain outside of the keep-in zone.

to the ridge after the drive step completed; a portion of the steered left front wheel is visible on the left side of the right-most image. AutoNav determined Curiosity was too close to the hazard to continue and set a NO_PATH drive fault, which resulted in a mobility goal error. This fault protection category is a safety feature that prevents further driving if the rover is too close to an obstacle.

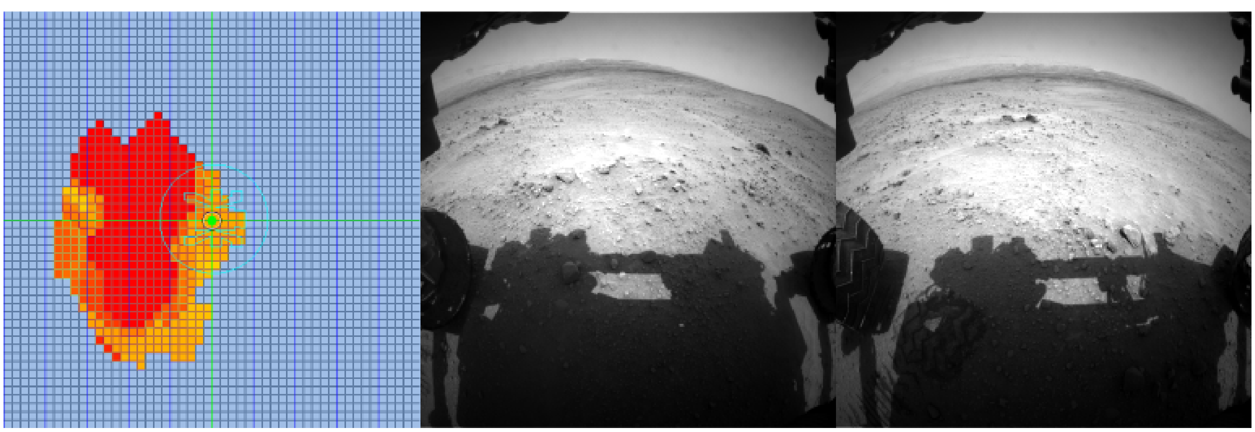

Figure 30: Sol 677 final rover-centered, auto-generated terrain World Map (left), the corresponding left front HazCam image (middle), and the left front HazCam image after the next drive step (right). Curiosity was driving to a navigation goal in the direction of the left side of the World Map. AutoNav took a sharp turn to the left to avoid the ridge in front of it in the middle image. After the drive step, AutoNav determined Curiosity was too close to the hazard to continue and stopped the drive 36.8 meters short of the navigation goal. The map size is 10x10 m^2 and the resolution of each map cell is 40x40 cm^2. Map cells with a color close to red are not traversable.

7.3.2 Non-geometric hazard (slip-based) faults

Wheel slip fault protection

Wheel slip is dependent on terrain tilt and wheel/terrain interactions. Wheel-slip fault protection is enabled by default, with nominal limits of 60% for a single occurrence and 40% for two consecutive occurrences. But the operations team will change the slip fault protection parameters as appropriate for the terrain and drive objectives, based on experience from previous drives and science and engineering team predictions for the planned drive. The allowed slip ratios set upper bounds on the rover's position uncertainty at any given step; that uncertainty influences how close a planned drive can get to an obstacle. Figure 31 contains sol 2086 and 2087 NavCam images of the terrain where the maximum Curiosity wheel slip occurred, and Figure 32 shows a visualization of the drive path incorporating VO corrections. The sol 2086 forward drive faulted due to excessive wheel slip of 64.8%. Factors in the high wheel slip were a flat steep rock under the RR wheel, a ridge in front of the RF wheel, and an uphill rover tilt of 18.1°. The operations team increased the single occurrence slip limit to 90% for the forward drive on the next sol (2087), but that drive faulted with excessive wheel slip of 98.7%. On sol 2089, Curiosity successfully escaped the hazard by backtracking 1 meter and taking a different route forward. Exceeding the wheel slip limit has caused 11 drive faults on sols 402, 465, 672, 710, 923, 978, 983, 984, 1703, 2086, and 2087.

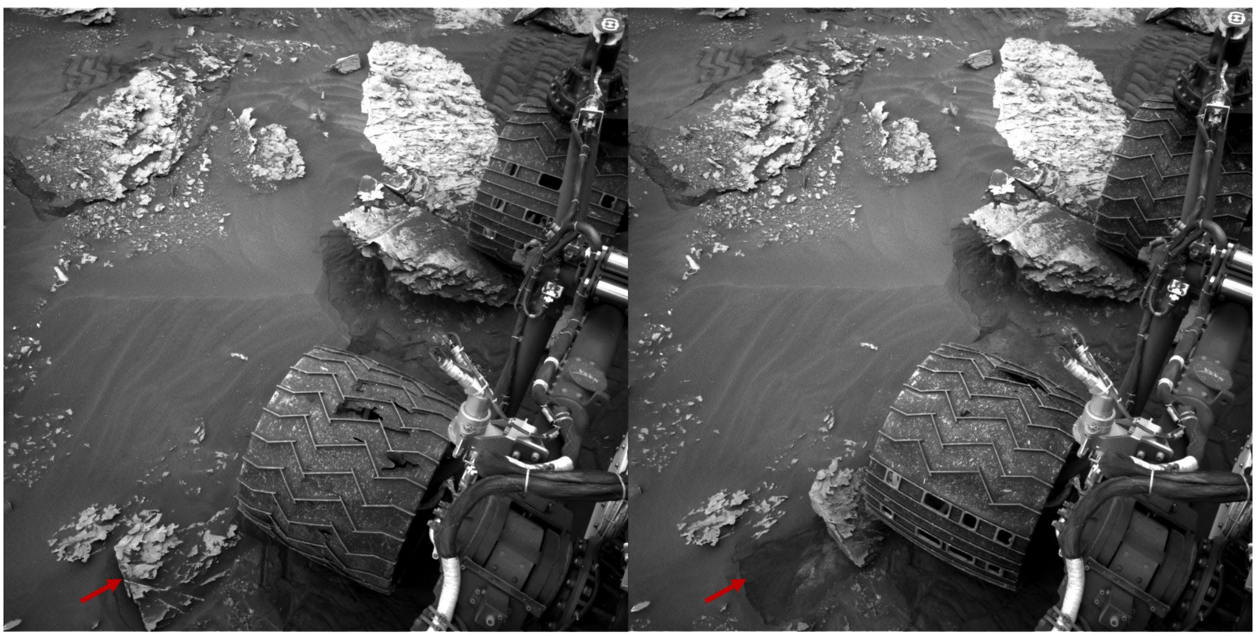

Figure 31: NavCam images of the RM and RR wheels on sols 2086 (left) and 2087 (right). The sol 2087 forward drive faulted when 98.7% wheel slip occurred, exceeding the 90% limit set for this drive. No forward progress was made. Note that a rock was dragged backward by the RM wheel.

Keep-out and keep-in zones

RPs use 2D Keep-out and Keep-in zones to indicate known hazards (including non-geometric hazards like sandy terrain) and specify corridors of safety. The onboard mobility software guarantees that the rover will never choose to enter any area declared off-limits by the combination of Keep-in and Keep-out zones; any such attempt will raise a mobility goal error and cause that command to fail without commanding that motion. When used in combination with VO for precise positioning, they enable the rover to stay out of dangerous areas even in the presence of unexpected slip. Zones can be specified as circles, oriented rectangles or triangles. Attempting to violate a keep-in boundary has caused 2 drive faults (sols 163 and 324) due to rover slip. As illustrated in Figure 33, the sol 324 drive faulted after 18 meters of backwards driving as the rover drifted off course towards the boundary of a narrow keep-in zone.

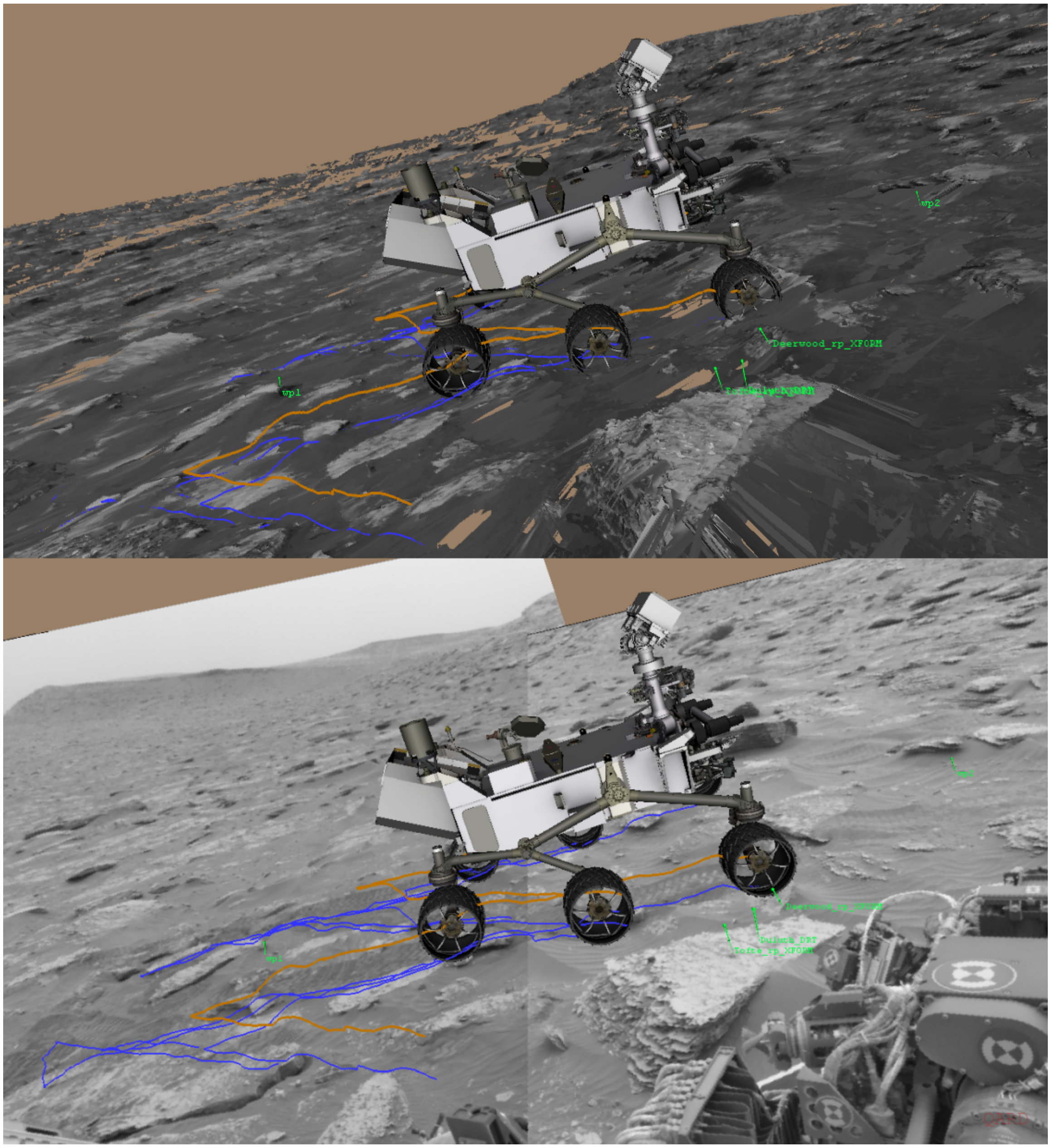

Figure 32: Visualizing the Sol 2086 drive, which failed due to high wheel slip. The upper image shows the actual rover path projected into the "planning mesh," a visualization of the terrain used by RPs to create drive command sequences. Orange lines track the wheel centers, blue lines track the lowest point on the wheel (i.e., ground contact). The lower image shows the same data projected into NavCam images taken on sol 2089, after the drive completed. Actual drive tracks are visible in the lower image. Images rendered by the rover planning tool RSVP.

After the initial discovery of the wheel wear problem, a ground-based machine learning terrain classification system was developed and deployed to assist the operations team in performing their assessment of Keep-out areas (Ono et al., 2015). And related work proposes to perform similar analyses as part of onboard processing, e.g. (Angelova et al., 2007; Rothrock et al., 2016). But since the science team successfully identified and selected terrains safer for the wheels since then, Keep-out zones have generally been specified by RPs by hand, based on visual terrain cues evaluated by them, their full suite of ground analysis tools, and the Surface Properties Scientist.

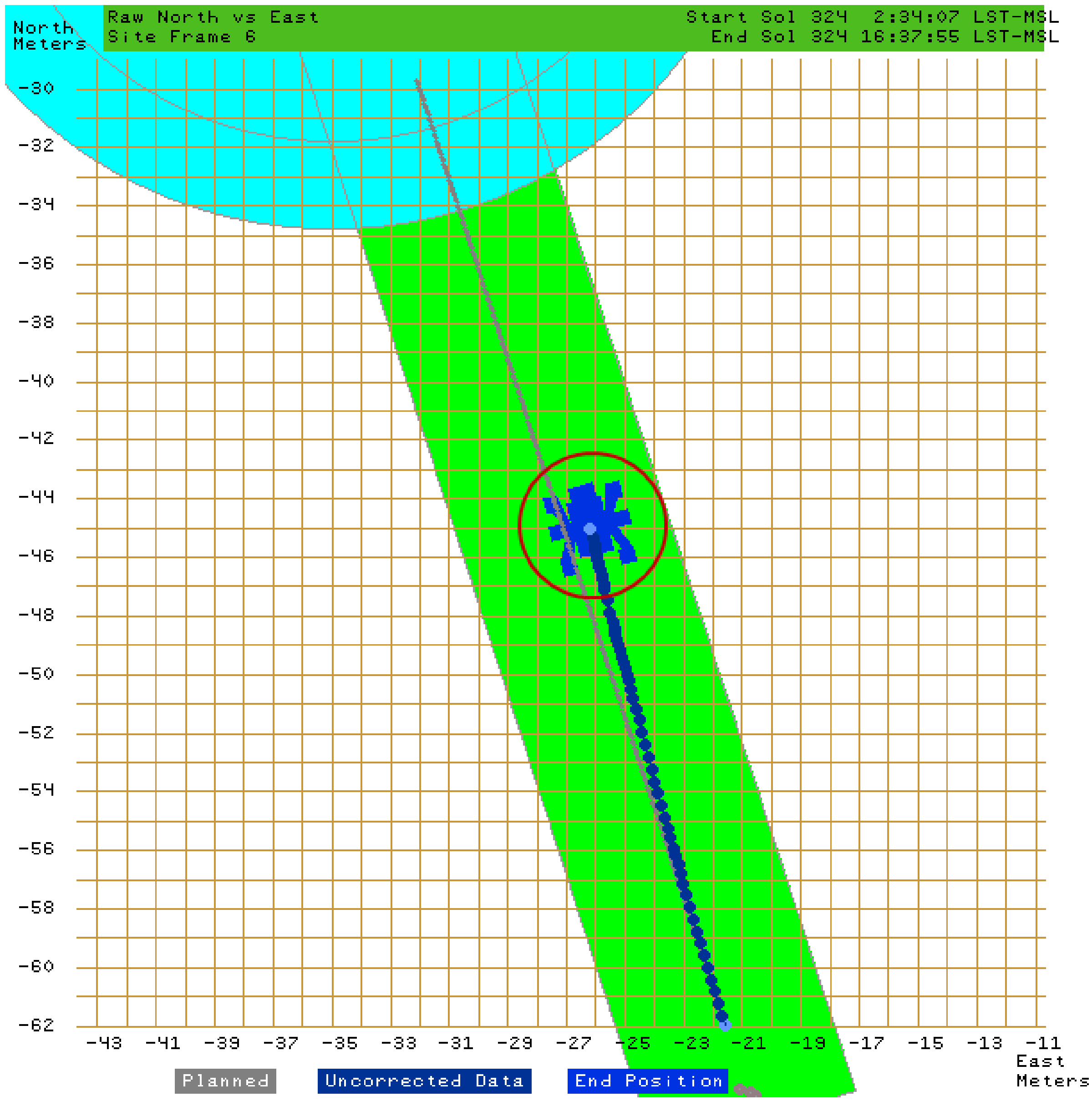

Figure 33: Course plot of the sol 324 drive auto-generated by ground tools for mobility performance assessment. The sol 324 drive stopped after 18 meters of backward driving with a keep-in zone violation because mobility fault protection determined the next drive step would cause a 2.5 meter radius around the rover to intersect the boundary of the green keep-in zone. The red circle with a 2.5 meter radius was overlaid on the course plot to illustrate how close the rover was to the edge of the keep-in zone. Grid lines in the map indicate 1 meter spacing.

VO failure to converge

The operations team can choose to set a maximum number of allowable VO failures to converge. Setting such a limit is a helpful way to bound the amount of position uncertainty that must be evaluated for any given sol's drive plan (by limiting the number of steps that can accumulate unknown and uncorrected slip). Although VO works very well in general, it depends on there being enough features detected in the nearby terrain to enable their motion to be tracked. If any of its internal sanity checks fails or the terrain lacks sufficient features, it can fail to converge, e.g., as in Figure 34. The largest number of failures that have occurred on a single sol is 11 (sol 2434). The 11th VO failure caused a mobility goal error to be declared and the drive to stop due to the VO failure limit of 10 having been exceeded. VO failures have caused 5 drive faults on sols 1035, 1042, 2304, 2434, and 2447.

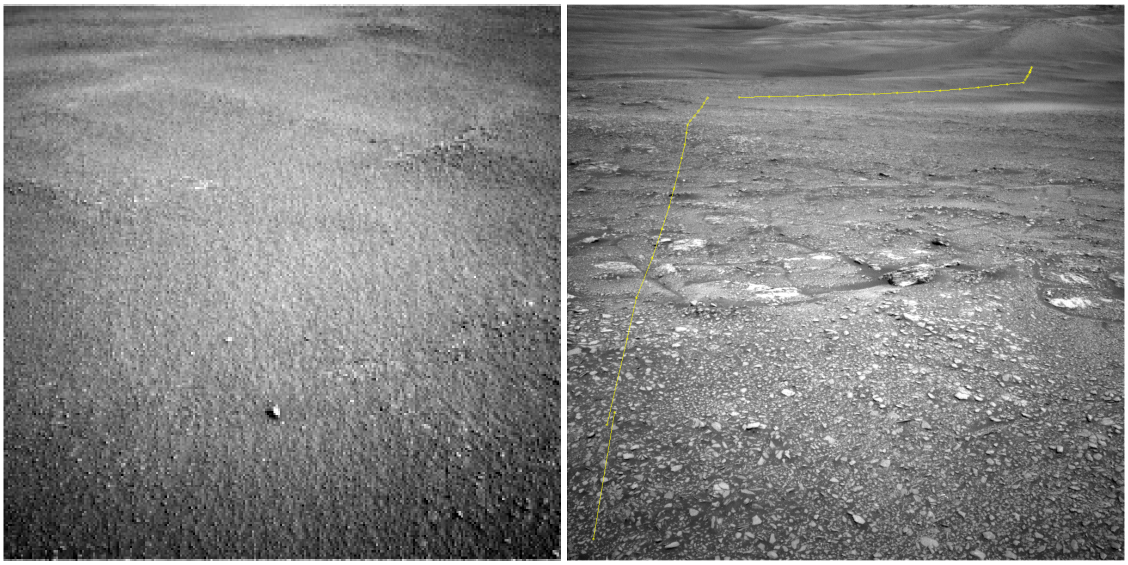

Figure 34: NavCam VO image and overall drive path from sol 2434 on terrain with a lack of autonomously detectable and trackable features. The max number of VO failures in a single drive (11) occurred here. Low expected wheel slip on this terrain, and a lack of hazards near the planned path, led the RPs to set the max allowable number of VO failures to a high number. The max wheel slip measured during the drive was 13.5%. The yellow points show the path taken by the rover origin, plotted in a planning NavCam image taken two sols before the drive.

7.3.3 Reactive Mobility Faults

Suspension fault protection

Curiosity uses a passive rocker-bogie suspension system (Bickler, 1998). The angles measured by that system are determined by the interaction of the rover with local terrain. When drives are planned in the RSVP tool, simulated suspension angles are determined by "settling" the rover onto the simulated terrain. RPs then interrogate that series of simulated angles to determine the minimum and maximum angles expected to be encountered on a given drive. If the actual angles were to exceed those bounds, that would indicate a mismatch with the plan (e.g., that the rover has drifted off course, or that the simulated terrain wasn't a good match for the actual terrain). So every drive sol includes an updated set of min/max suspension angles that are anticipated for the drive; should any angle fall outside those bounds, a motion error will be raised.

Curiosity suspension angles up through sol 2488 are shown in Figure 35. The max bogie and differential angles experienced by Curiosity are 25.2 and 9.4°, respectively. The nominal flight bogie and differential angle limits are 17 and 7°, respectively. Exceeding a suspension limit has caused thirteen drive faults on sols 102, 713, 1053, 1066, 1110, 1296, 1376, 1438, 1471, 1485, 1664, 1684, and 1751. During the suspension limit fault on sol 1751, illustrated in Figure 36, the right bogie reached an angle of 17.5°out of an allowable 17°as the RM wheel climbed a tall rock.

Since the suspension system is passive, it is possible for a middle or rear wheel to lift off the terrain for a prolonged amount of time, if sufficient tension has built up in the suspension. For example, on sol 313, the LM wheel popped a wheelie during the final drive command to straighten the front and rear wheels. During that command, the left bogie angle increased 11.9°, lifting the LM wheel off the terrain. On sol 317, the LM wheel was driven while still in a wheelie and the no load current was determined to be approximately 0.16 A.

TRCTL includes a wheelie suppression algorithm that watches for consistently growing bogie suspension angles above a threshold with a corresponding wheel that requires little current to turn. If this is detected, the speed of the other wheel on the bogie is adjusted to correct the condition and maintain six wheels in contact with the terrain. By default, the TRCTL wheelie suppression algorithm is enabled when TRCTL is enabled (Toupet et al., 2020).

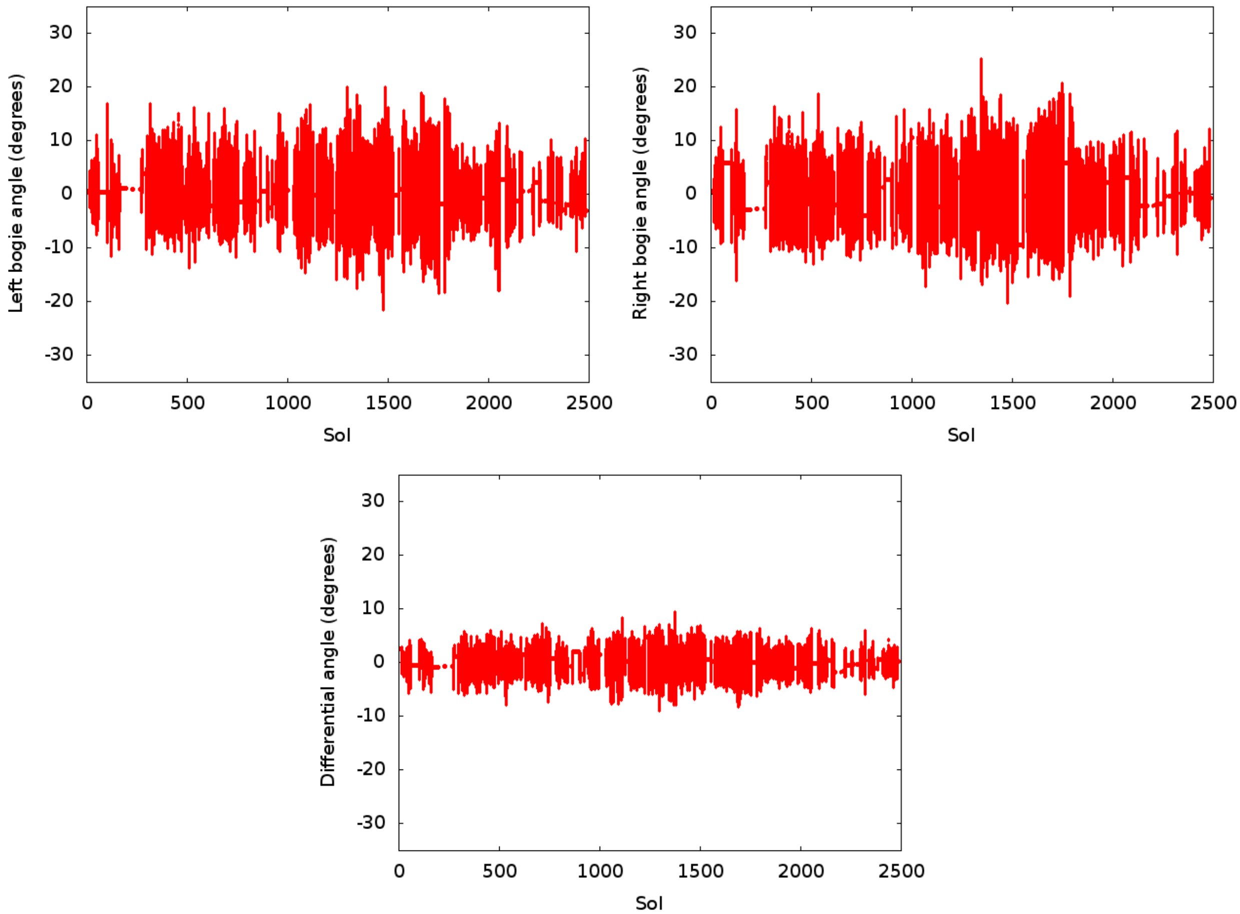

Figure 35: Curiosity suspension angles during the first seven years of the mission. The plot illustrates the passive suspension constantly reacts to the terrain profile, which has not been planar.

Pitch and roll fault protection

As with the suspension fault protection, when drives are planned in the RSVP tool, simulated pitch and roll angles are determined by "settling" the rover onto the simulated terrain. RPs then interrogate that series of simulated angles to determine the minimum and maximum angles expected to be encountered on a given drive. If the actual angles were to exceed those bounds, that would indicate a mismatch with the plan (e.g., that the rover has drifted off course, or that the simulated terrain wasn't a good match for the actual terrain). So drive sols may include a set of min/max pitch and roll angles that are anticipated for the drive; should any angle fall outside those bounds, a motion error will be raised. These are not always enabled (though Tilt fault protection *is* always enabled), generally these are only used when a particular pitch or roll is important to the drive (e.g. when approaching terrain with an abrupt slope change).

Curiosity pitch and roll angles up through sol 2488 are shown in Figure 37. Rover pitch and roll are measured in a local level frame where x is forward, y is to the right, and z is down. Therefore, positive pitch corresponds to the forward side of the rover moving upward and positive roll corresponds to the left side of the rover body moving upward. The max absolute values of pitch and roll angles experienced by Curiosity are 25.22 and 20.69°, respectively. Rover pitch and roll fault protection are disabled by default, but can be enabled on a drive-by-drive basis. The nominal flight pitch and roll limits are +/-15°. Pitch fault protection has been enabled on seven sols (817, 1035, 1037, 1049, 1051, 1262, and 1371). Roll fault protection has been enabled on two sols (1260 and 1311). Exceeding the rover pitch min or max limit has caused two drive faults on sols 1049 and 1262. During the pitch limit fault on sol 1049, illustrated in Figure 38, the rover pitch angle reached an angle of 15.19°out of an allowable maximum of 15°as the rover climbed a ridge.

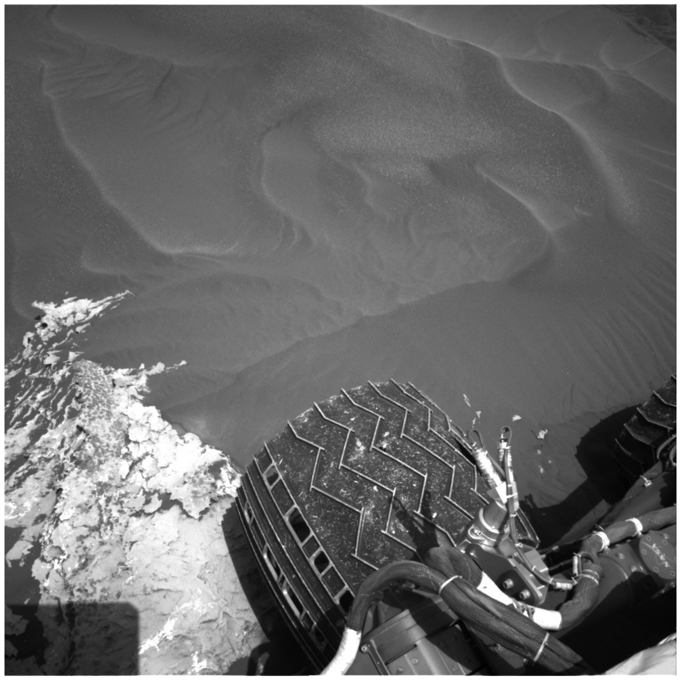

Figure 36: NavCam image acquired after the sol 1751 drive faulted when the right bogie angle exceeded the bogie limit of 17°due to the RM wheel (in the center of the image) traversing a tall rock. The RR wheel is to the right of the image.

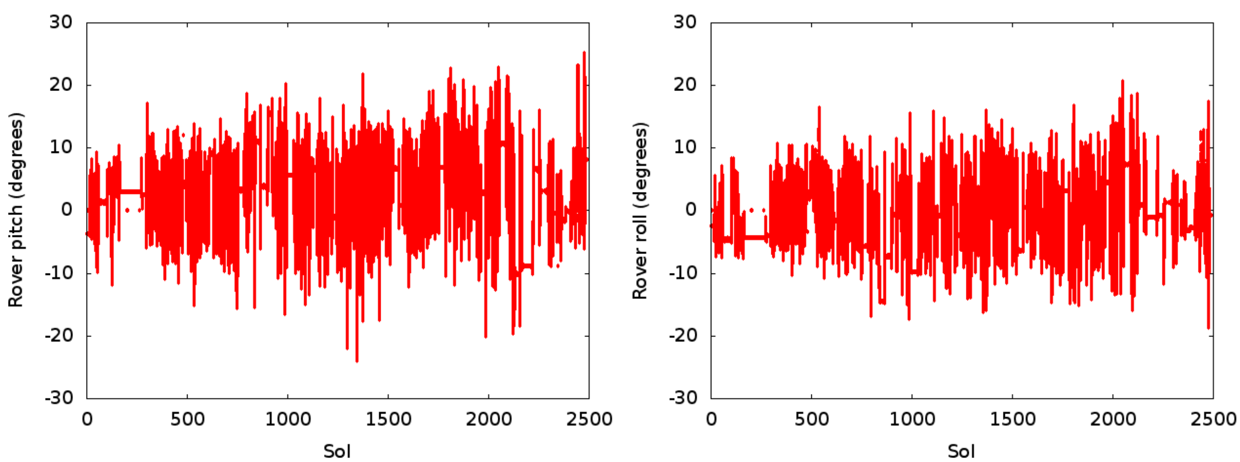

Figure 37: Curiosity pitch and roll angles during the first seven years of the mission. The max absolute values of pitch and roll angles experienced by Curiosity are 25.22°and 20.69°, respectively. Rover pitch and roll fault protection are disabled by default, but can be enabled on a drive-by-drive basis. When enabled, the pitch and roll limit for a drive is typically set to slightly higher than the max pitch and roll of the simulated drive. There have been no drive faults due to the roll limit. Exceeding the pitch limit has caused drive faults on two sols (1049 and 1262). The pitch limit on those sols were 15.0°and 6.0°, respectively.

Tilt fault protection

The rover tilt, which is the angle between the rover body z axis and the gravity vector, is estimated from onboard accelerometers for the purpose of tilt fault protection. Accelerometer data is noisier than the integrated gyroscope measurements used for nominal attitude estimation, but since it is a direct measurement, it is not subject to long-term accumulated bias. Curiosity tilt angles up through sol 2488 are shown in Figure 39. The max tilt angle experienced

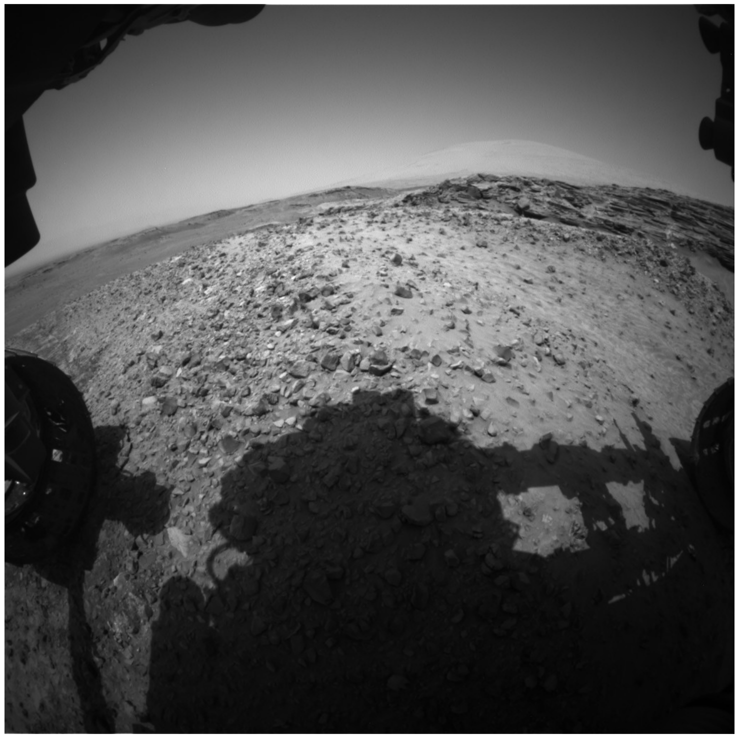

Figure 38: Front HazCam image acquired after the sol 1049 drive faulted when the rover pitch angle exceeded the max limit, which was set to 15°.

by Curiosity is 25.34°. Tilt fault protection is enabled by default, and the nominal flight tilt limit is 30°. However, the tilt limit is typically lowered for each drive, based on the max predicted tilt experienced in the simulation of the planned drive. Exceeding the tilt limit has caused three drive faults. During the tilt limit fault on sol 472, illustrated in Figure 40, the rover tilt angle reached an angle of 12.3°, exceeding the allowed maximum of 12°over 4 contiguous 8 Hz samples, as the rover drove uphill. The maximum rover tilt that was expected from the simulation of the drive was 8°.

Yaw fault protection

Curiosity yaw angles up through sol 2488 are shown in Figure 41. Rover slip can cause significant changes in the rover heading, particularly if the slip mostly occurs on the wheels on one side of the rover during open-loop arc motions. Setting upper and lower limits on the expected yaw for each leg of a drive enables such slip to be detected quickly by the onboard attitude estimator, stopping the drive as soon as the limit is exceeded. Exceeding the yaw limit has caused 4 drive faults on sols 676, 683, 1689, and 1789. The sol 676 and 1789 yaw-limit drive faults occurred while driving on sandy terrain. The sol 683 yaw-limit drive fault occurred when AutoNav caused the rover to make a turn to avoid an obstacle. (AutoNav is not aware of the yaw limits.) The sol 1689 yaw-limit drive fault was caused by an operations failure to properly set the yaw limits in the drive sequence. Figure 42 illustrates the sandy terrain where wheel slip caused a 30°change from the desired rover heading on sol 1789. Unintended yaw can also occur when driving on rocky terrain, for example, if a wheel slips off a rock; if one or more rocks move while being traversed; or if a part of the wheel above ground interacts directly with the terrain (e.g. scraping a rock it passes, or passing through a nearly-wheel-sized rut).

Actuator stalls

On seven occasions, Curiosity has experienced a stall condition of either a steering motor or wheel motor. This occurs when the motor stops turning prior to reaching its commanded position. Like all mobility faults, this will stop further

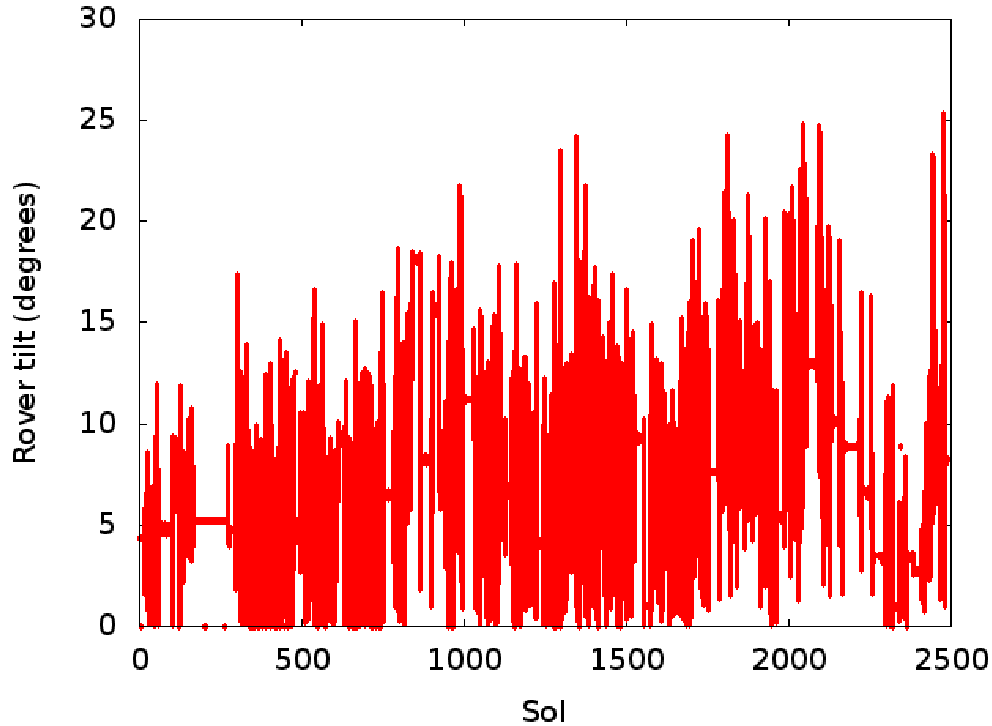

Figure 39: Curiosity tilt angle during the first seven years of the mission. The max tilt angle experienced by Curiosity was 25.34°, occurring on sol 2477. The tilt limit for each drive is typically set to slightly higher than the max tilt of each simulated drive. Exceeding the tilt limit has caused drive faults on three sols (151, 309, and 472). The tilt limit on those sols were 6.9°, 12.0°, and 12.0°, respectively.

driving until a command is sent to re-enable mobility. Wheel interactions with rigid terrains can cause this condition, as well as possibly a motor under-producing required torque due to inaccurate current control or incorrect motor commutation, should there have been motor backdriving when its relative encoder was previously not monitored. This has occurred on sols 295 (RF steer), 333 (LR steer), 455 (RF steer), 1267 (RR drive), 1843 (RR steer), 2003 (RM drive), and 2051 (RR steer).

A related fault condition is "slow overcurrent," where a motor is consistently drawing more current than usual for a longer period of time, and may be overheating or adversely interacting with soft terrain. This would still be below the instantaneous current limit for the motor, which may be needed and is not a problem for a short amount of time. This condition has only occurred once on sol 1616, when the RR steering current exceeded the current limit of 2.5 A for 2 seconds, resulting in a RR steering stall.

7.3.4 Goal Error Faults

Command timeout

A duration limit can be set on individual mobility commands. If the command execution exceeds the duration limit, the drive is stopped with a motion error. Duration limits can prevent a turn-in-place from executing indefinitely while the wheels are slipping and embedding. As illustrated in Figure 43, exceeding the duration limit for a turn-in-place command has caused 1 drive fault (sol 711). Other duration limits that have caused drive faults are exceeding the duration limit during execution of 1) an arc with TRCTL enabled (sol 1786), and 2) a go to waypoint motion (sols 426 and 896).

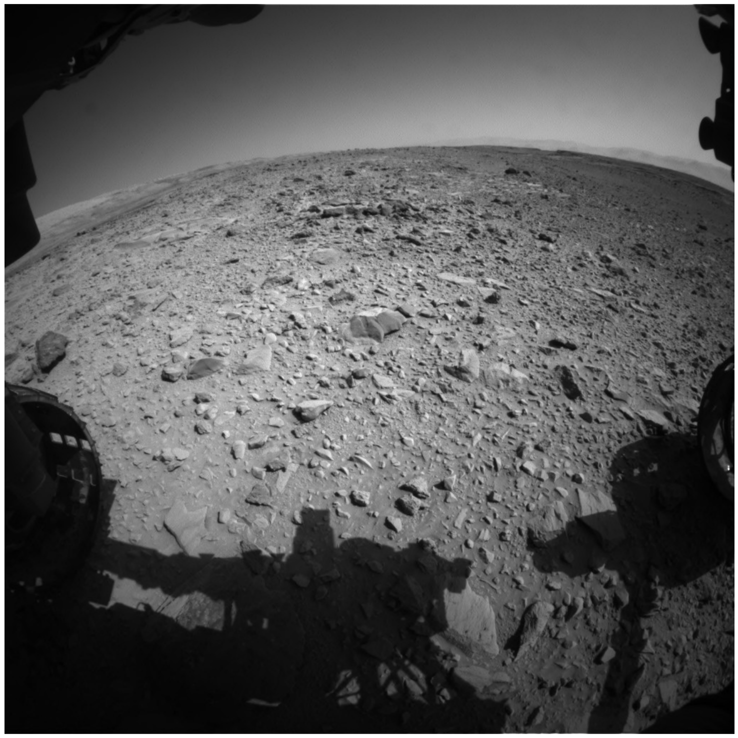

Figure 40: Front HazCam image acquired after the sol 472 drive faulted when the rover tilt angle exceeded the max limit, which was set to 12°.

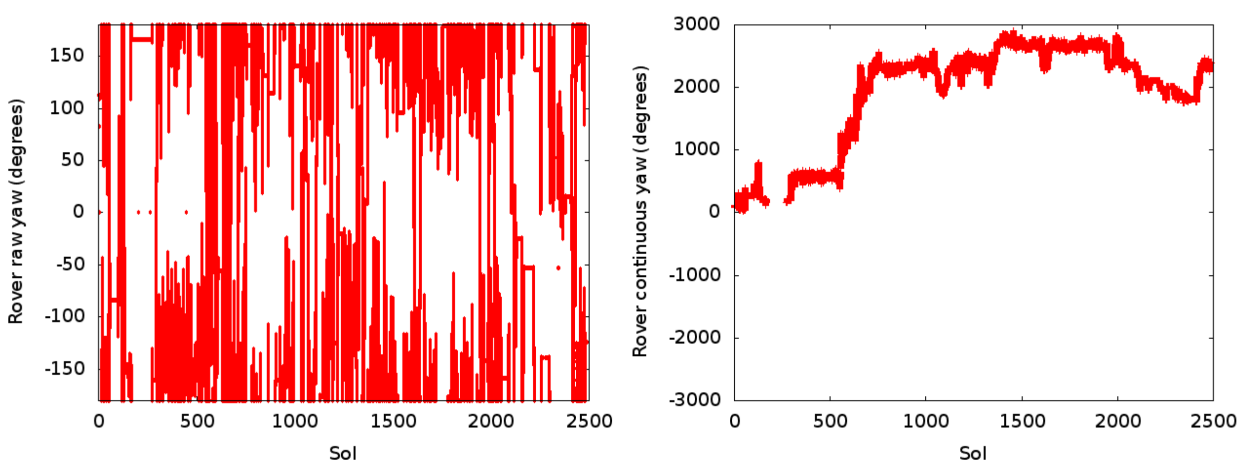

Figure 41: Curiosity raw yaw angles (left) and continuous yaw angles (right) during the first seven years of the mission. North corresponds to a heading of 0°. Increases in heading corresponds to turning to the right and decreases in heading corresponds to turning to the left. From sol 546-671, driving was predominantly backwards. During that period, the continuous yaw plot reflects a preference to turn to the right to avoid occlusions from the rover when acquiring post-drive images from the NavCams for planning the next drive. The cumulative turning performed by Curiosity is equivalent to 6.3 revolutions to the right.

Limit Cycle

A Limit Cycle fault is raised whenever the rover commands a relatively large amount of motion (e.g., 4.5 meters), yet only achieves a much smaller amount of progress in Euclidean distance (e.g., 2 meters). Originally developed as a way to stop the rover from driving back-and-forth again and again during autonomous hazard-avoiding drives, it had

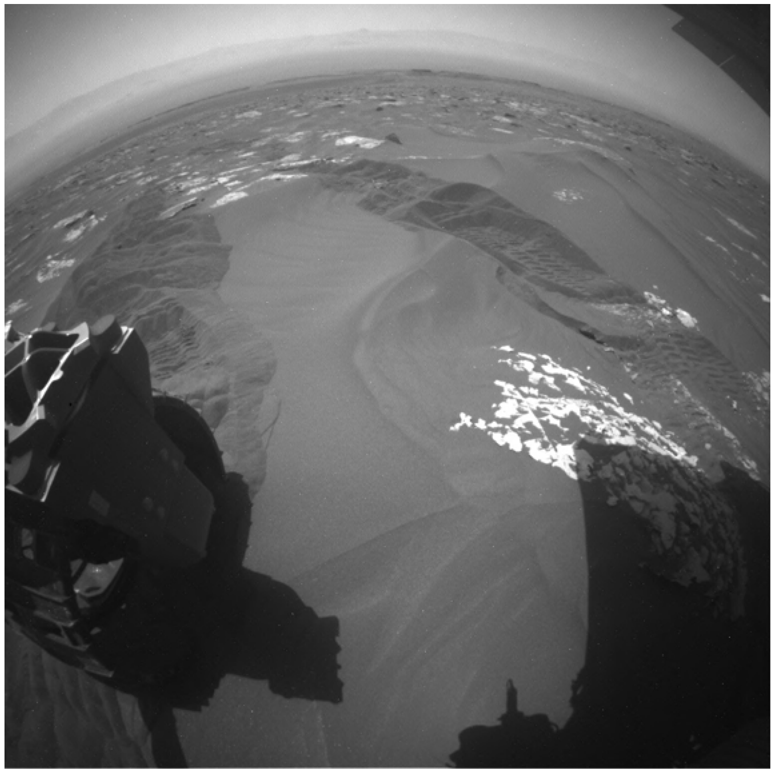

Figure 42: Rear HazCam image acquired after the sol 1789 drive. The RR wheel is visible in the image. High slip in sand caused Curiosity to exceed a 149.265 +/- 30°yaw limit, faulting the drive.

Figure 43: Sol 711 NavCam image of the RM and RR wheel after a turn-in-place command timed out. According to IMU data, the turn slip was 40.4%.

been left enabled during the very slippery drive through the polygonal ripple sands of Hidden Valley on sol 709 (see Figure 44). On that drive the rover encountered very high slip (45% growing to 77.5% over seven steps), resulting in very slow progress, and that triggered the only instance of the Limit Cycle fault thus far. Although this demonstrates Limit Cycle can function as a wheel slip detector, we have since relied on the Fast and Slow Slip fault behaviors instead.

On sol 710, we continued to try to drive through the polygonal ripple sands at Hidden Valley. After commanding over 17.35 meters but only achieving 7.78 meters of actual motion, the drive faulted because the Slow Slip limit of 70% was exceeded on five consecutive drive steps. During excessive slip, there is a risk of excessive wheel sinkage. There are no sensors onboard Curiosity that can measure wheel sinkage directly; wheel sinkage is estimated by the operations team through inspection of images of the wheels. On sol 711, the robotic arm was unstowed and under-belly MAHLI images of the wheels were captured to assess wheel sinkage. Figure 45 contains a MAHLI image of the RM and RR wheels. Approximately 7 grousers are embedded in sand on each wheel, which corresponds to approximately 9 cm wheel sinkage.

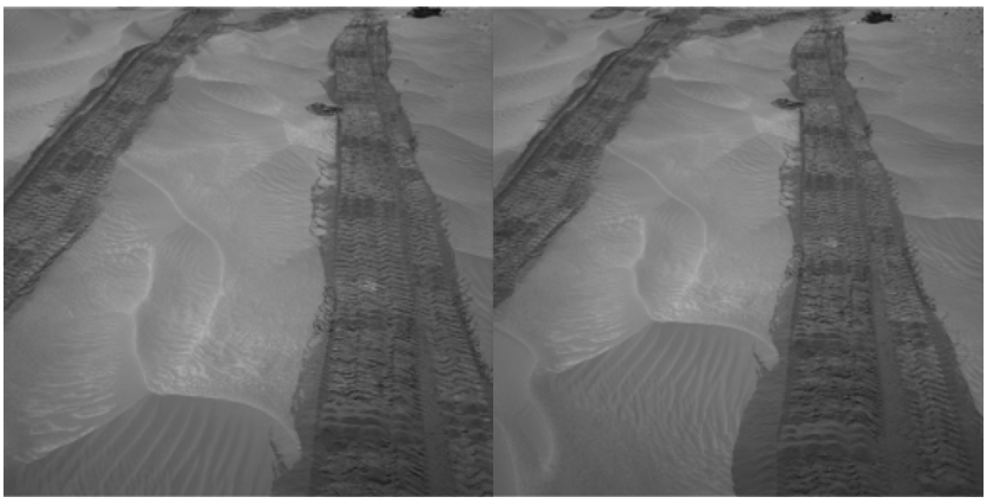

Figure 44: NavCam VO images of wheel tracks from sol 709. The commanded drive distance between the left and right image was 2 meters, but the actual distance covered was 0.54 meters. Because Curiosity was not making enough progress towards the navigation goal, a limit-cycle drive fault was declared. During the final step of the drive, the wheel slip was 77.5%, below the 90% single occurrence limit set for this leg of the drive.

Previous Drive Failure

When multiple drives are planned without ground in-the-loop in between the drives, if the first drive ends with a fault, the additional planned drives are precluded. Multiple drives without ground in-the-loop between them can be planned on a single sol or over multiple sols (e.g., over a non-planning weekend or holiday). There have been two occurrences of this type of drive failure. The sol 296 and 456 drives were precluded because the drives on the previous sols ended early with a RF steer stall.

8 Actuator Health

The qualified life cycles for the WSAs is 15,000 revolutions (i.e., revolutions for 1x life). During MSL pre-launch testing at JPL, a WSA was tested to 2x life, disassembled and inspected, and no failure was observed. Figure 46 shows the total number of actuator revolutions for each WSA onboard Curiosity.

The six drive actuators are independently controlled. The maximum number of Curiosity drive actuator revolutions has ranged from 15,253.0 to 15,716.4 revolutions, slightly above 1x life of 15,000. Note that the middle drive actuators have experienced slightly fewer revolutions than the front and rear drive actuators. Because the middle wheels are

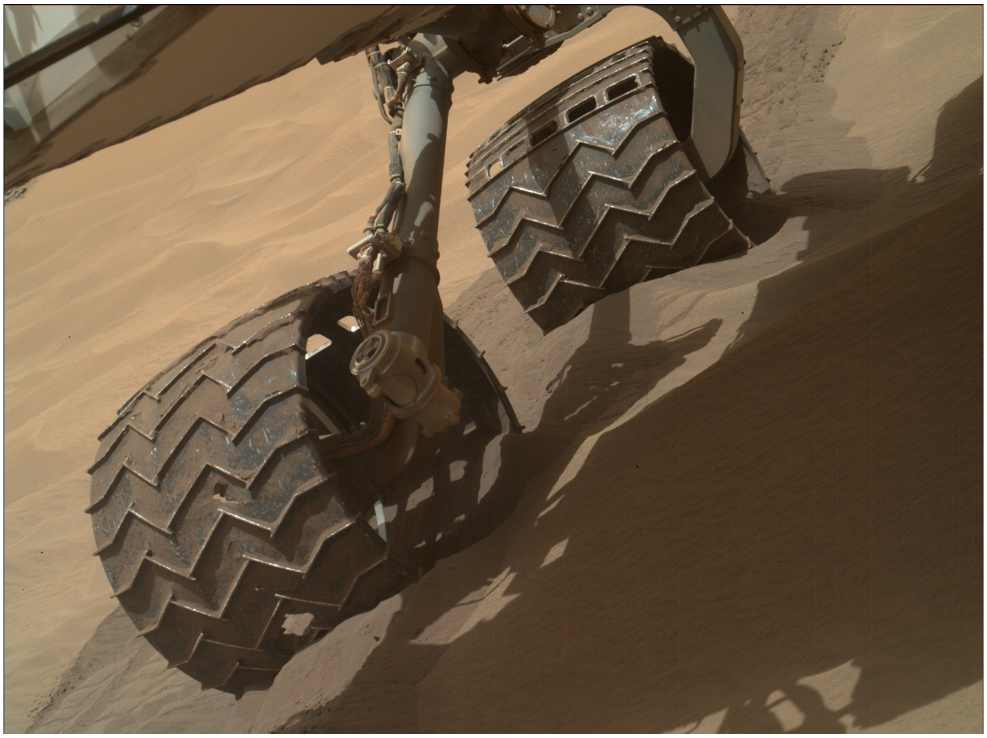

Figure 45: On sol 711, an under-belly MAHLI image of the wheels was acquired to assess wheel sinkage.

closer to the instantaneous center of rotation than the front and rear wheels, they revolve less during turns-in-place and non-straight arcs.

The four steer actuators are also independently controlled and have a hard limit of +/-95°and a software limit of +/-85°, both of which are measured as angles from the rover's longitudinal axis. Steering is performed much less frequently than driving. The number of Curiosity steering actuator revolutions has ranged from 596.7 to 643.8 revolutions, approximately 3.8% of their 1x life. The numbers of revolutions for the rear steering actuators are slightly less than the front steering actuators. Since the rear wheels are closer to the middle wheels than the front wheels, they steer to a slightly smaller angle than the front wheels during a turn-in-place.

For each drive and steer step, flight software calculates the motor current mean and standard deviation over all 64 Hz samples from each WSA and records it in mobility telemetry. In Table 9, the middle column contains the mean of the current mean for each drive and steer step, and the right column contains the mean of the current standard deviation for each drive and steer step. These values are in comparison to the approximate no load current of 0.16 A, measured on sol 317 while the LM wheel was in a wheelie state. It is not surprising that the rear-wheel drive currents have been higher than the other drive actuators, given that most Curiosity's driving has been uphill in the forward direction. The number of RF drive steps is larger than the other drive actuators because the RF wheel has been used to scuff terrain on several sols (e.g., sols 57, 799, 1221) in preparation for below-the-surface imaging and Alpha Particle X-Ray Spectrometer (APXS) measurements.

As of sol 2488, we have experienced 2 drive actuator stalls (sols 1267 and 2003) and 6 steer actuator stalls (sols 295, 333, 455, 1616, 1843, and 2051). The most recent three steer stalls have occurred on the RR steer actuator, likely a coincidence since there have been no further stalls over the last 437 sols. As shown in Figure 47, the max current during all WSA stalls was under 4.0 A. As shown in Figures 48 and 49, over all drives, the maximum drive and steer actuator currents have been 4.422 and 3.594 A, respectively, well below the 10 A max current rating for the WSA. The low number of steer actuator revolutions leads to high confidence in their continued usage for years to come. There is also confidence in the continued usage of the drive actuators for years to come, given the successful test of a WSA to 2x life without any failure,

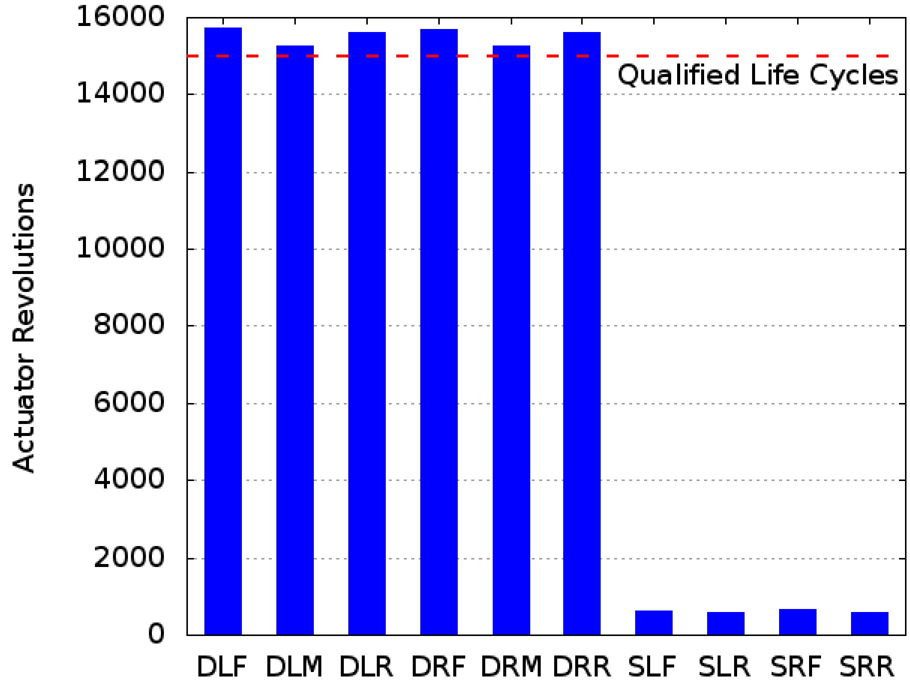

Figure 46: Drive and steer actuator revolutions as of sol 2488. DLF=drive left front, DLM=drive left middle, DLR=drive left rear, DRF=drive right front, DRM=drive right middle, DRR=drive right rear, SLF=steer left front, SLR=steer left rear, SRF=steer right front, SRR=steer right rear.

Table 9: Average motor current and current standard deviation for each WSA.

Actuator	Mean of current mean for each step (A)	Mean of current stddev for each step (A)
LF drive	0.317 (N=20778)	0.187 (N=20778)
LM drive	0.298 (N=20777)	0.168 (N=20777)
LR drive	0.345 (N=20778)	0.188 (N=20778)
RF drive	0.323 (N=20787)	0.189 (N=20787)
RM drive	0.275 (N=20778)	0.162 (N=20778)
RR drive	0.361 (N=20778)	0.191 (N=20778)
LF steer	0.253 (N=6981)	0.170 (N=6981)
LR steer	0.239 (N=6977)	0.163 (N=6977)
RF steer	0.246 (N=6988)	0.164 (N=6988)
RR steer	0.252 (N=6981)	0.169 (N=6981)

9 Wheel Health

On sol 490, the MSL team discovered a mission-threatening amount of damage to the rover wheels. As the rover had only driven 4.6 km of its 20 km design goal, it led to an investigation to understand and reduce the rate of damage in order to increase the longevity of the mission. Initial damage was found to be related to the interaction of previously-unseen terrain exhibiting small, sharp embedded rocks with the drive control mode of constant-speed six wheel drive actuators and the kinematics of the rocker-bogie suspension. Wheels leading a suspension pivot were forced onto the sharp, immobile surfaces by the other wheels as they maintained their commanded angular velocities (Arvidson et al., 2017a).

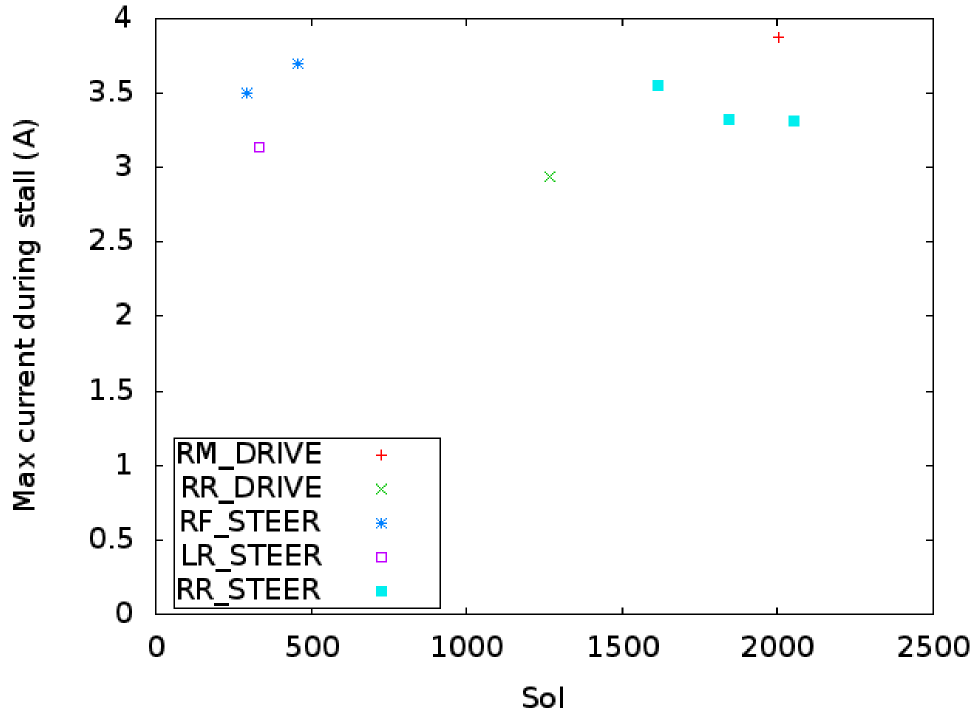

Figure 47: Each max actuator current measured during the 2 drive actuator stalls and 6 steer actuator stalls was always less than 4.0 A, well below the 10 A max current rating for the WSA. There have been no front drive actuator stalls during the mission. During the 435 sols prior to sol 2051, there were three RR steer stalls, but no RR steer stalls have occurred over the last 437 sols.

In response, a new algorithm known as TRCTL was developed (Toupet et al., 2020). It adapts each wheel's speed to fit the terrain topography in real-time, by leveraging the rover's measured attitude rates and rocker/bogie suspension angles and rates. When one wheel is going over a rock, the remaining wheels reduce their speed in order to not push or pull the rock-climbing wheel into the rock, reducing the forces on the wheel. On sol 1678 (April 24, 2017), TRCTL was approved for nominal use on Curiosity.

Figure 50 illustrates the usage of TRCTL since its approval for nominal use on Curiosity. Since sol 1678, 99.48% of the total odometry has had TRCTL enabled, and 93.75% of drive sols have had TRCTL enabled for at least a portion of the drive. Most of the non-TRCTL odometry since sol 1678 is from ten 1.256 meter drives (on sols 1682, 1730, 1798, 1887, 1989, 2030, 2115, 2296, 2407, and 2457) to capture MAHLI images of the entire surface area of the wheels in five equally spaced positions for wheel damage assessment. For those drives, TRCTL is disabled so each wheel turns the same amount, regardless of the profile of the terrain below the wheels. On sol 1800, TRCTL was disabled for 10.09 meters of the drive on terrain similar to where the sol 1786 TRCTL timeout occurred. Overall, 23.31% of Curiosity's odometry has been achieved while TRCTL was enabled. Table 10 summarizes TRCTL usage on Curiosity.

The images of the RM wheel in Figure 51 and the LM wheel in Figure 52 illustrate the damage done to the wheels since sol 490, including two grouser breaks on LM and one on RM. The new algorithm has empirically demonstrated reduction of wheel damage rates as predicted, at the cost of increasing drive duration by 10% on average and roughly doubling the drive motor history data volume.

One of the concerns of wheel damage is the possibility a shard of wheel skin could cut into the electrical cable to a drive actuator, causing the drive actuator to become uncommandable. The images in Figure 52 provide a good view of the path of the electrical cable to a drive actuator. Although it is theoretically possible that a section of wheel skin could crack along its neighboring grousers and bend inward far enough to reach the cable, it is considered a highly unlikely scenario. Inward-pointing flaps of wheel skin tend to break off long before they reach any significant length.

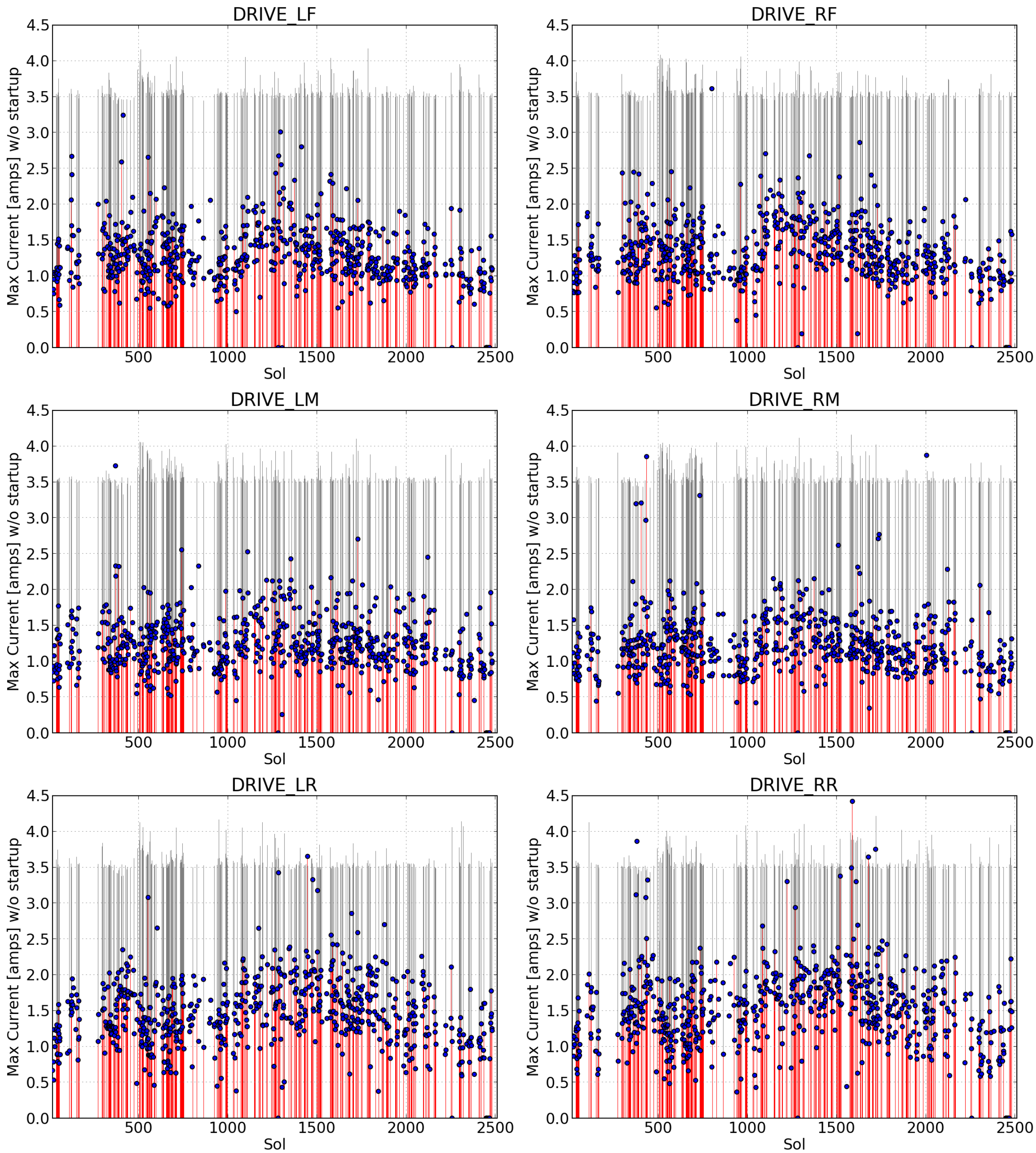

Figure 48: Max drive actuator currents per drive sol. Startup current during commutation for the first drive actuator usage on each drive sol is shown in gray. Max drive current on each drive sol due to wheel interaction with the terrain is shown in red, with a blue dot at the top of each red line.

Finite element analysis indicates that a flap of wheel skin long enough to reach the electrical cable would break off before it can cut the cable.

Testing conducted in the JPL Mars Yard without TRCTL software predicted a rate of grouser breaks that could result in unconstrained portions of the wheel contacting the electrical cable to its drive actuator some 20 km after the first grouser break occurred, shown in Figure 53. Based on that model, after accumulating 5 km beyond the first grouser

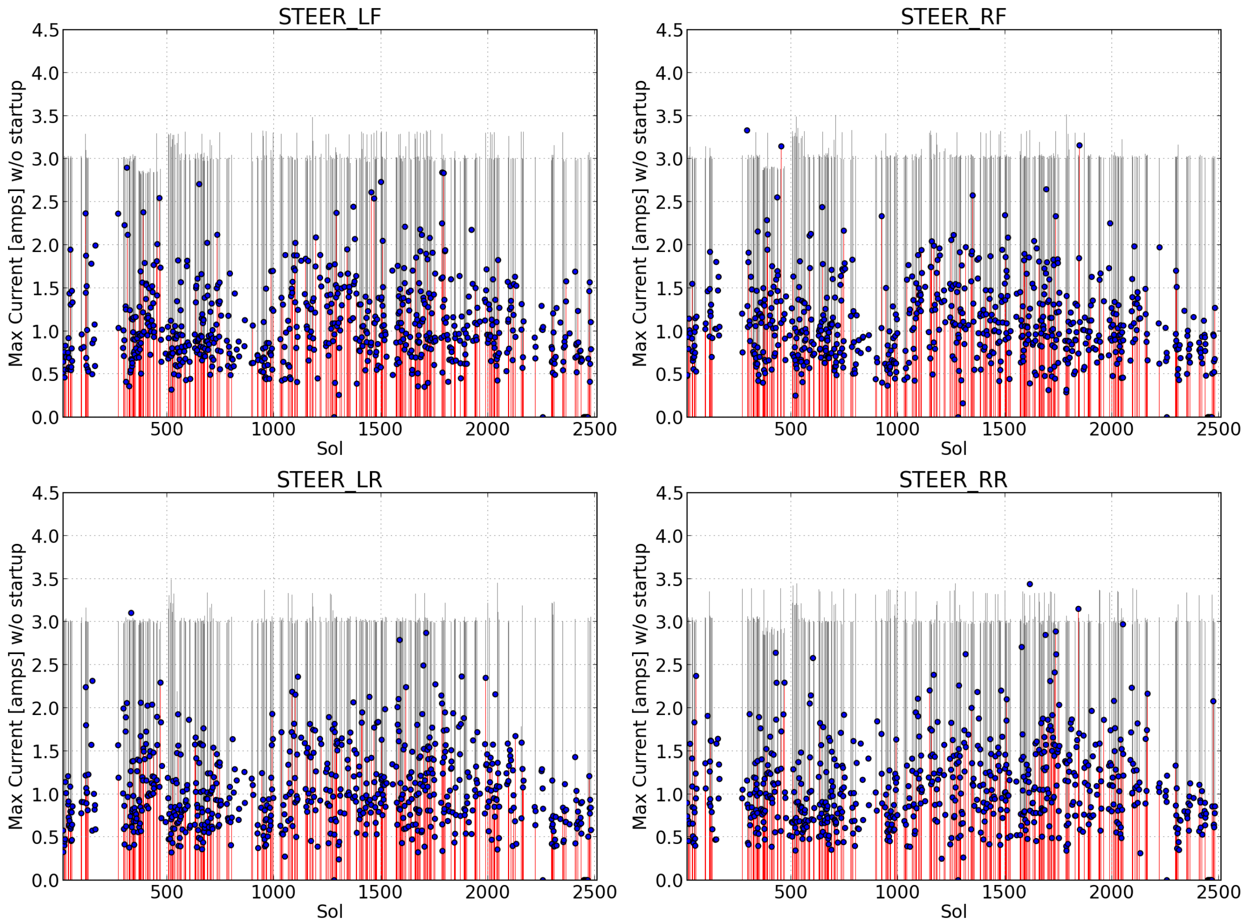

Figure 49: Max steer actuator currents per drive sol. Startup current during commutation for the first steer actuator usage on each drive sol is shown in gray. Max steer current on each drive sol due to wheel interaction with the terrain is shown in red, with a blue dot at the top of each red line.

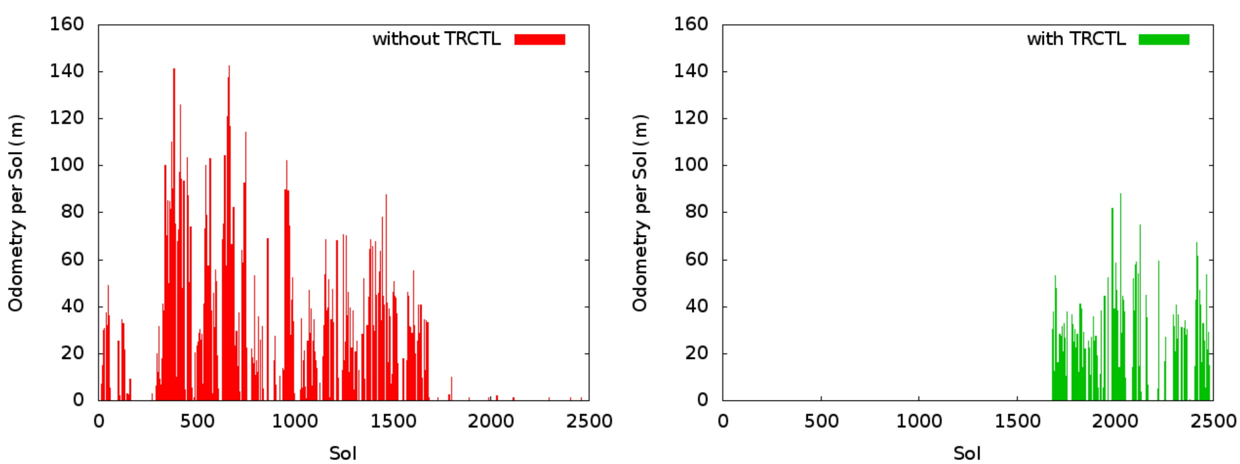

Figure 50: Since TRCTL was approved for nominal use on Curiosity on sol 1678, 99.48% of Curiosity's odometry has been with TRCTL enabled.

break, 4 grouser breaks were expected on a single wheel. However, as of sol 2488 and 5 km since the first grouser break on Mars, the number of breaks on the LM wheel is only 2 and on the RM wheel only 1. Both of the grouser

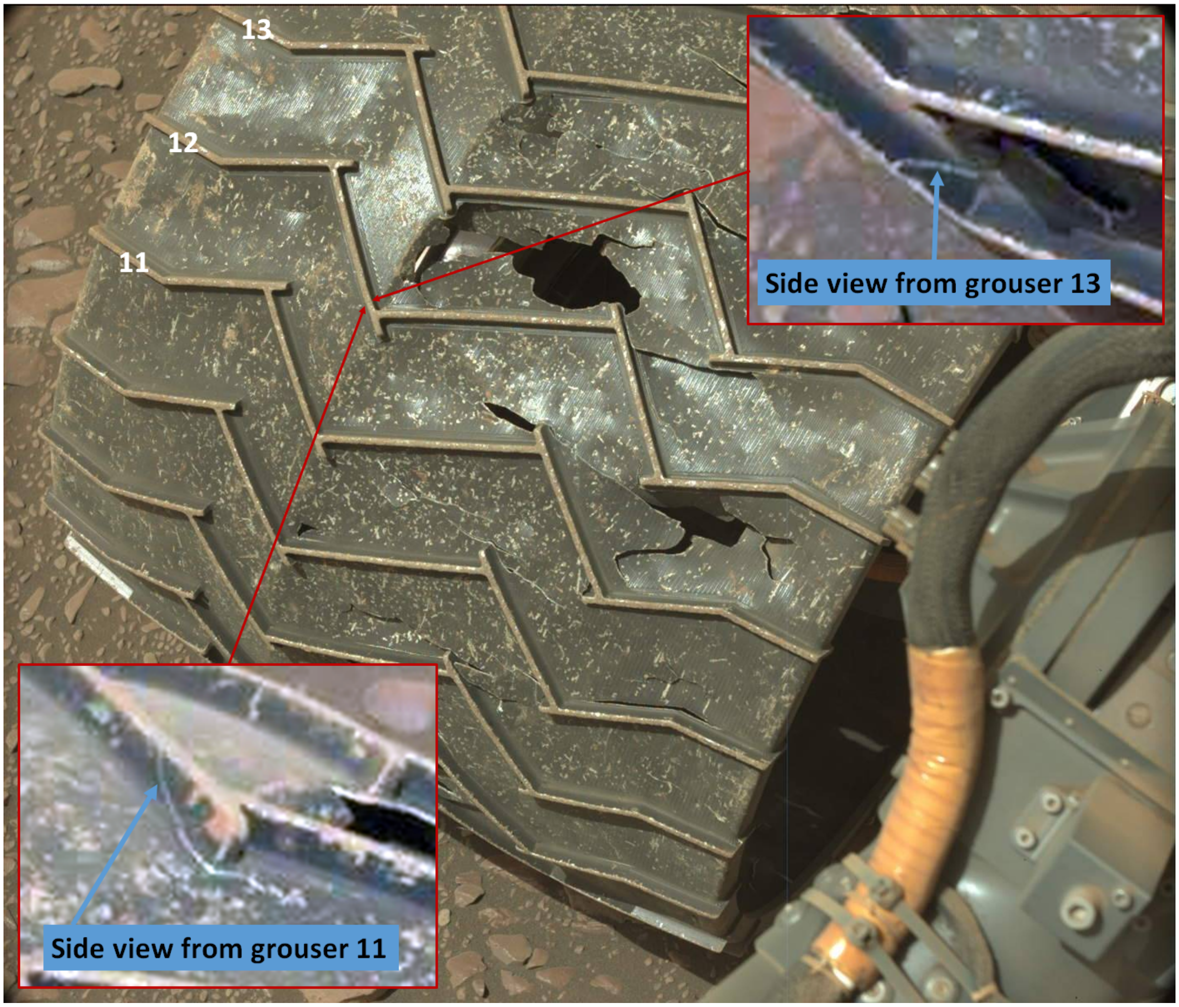

Figure 51: The single grouser break on the RM wheel is on grouser 12. It is visible from NavCam views of both sides of grouser 12, but not from an overhead view of grouser 12. Image Credit: NASA / JPL-Caltech / MSSS.

Table 10: Terrain-Adaptive Wheel Speed Control Usage Statistics

	Pre-TRCTL (sol 0000-1677)	**Post-TRCTL (sol 1678-2488)**
Mobility sols with some odometry	502	4 (TRCTL disabled) 199 (TRCTL enabled) 9 (both)
Odometry (meters)	16,323.9	26.0 (TRCTL disabled) 4,968.5 (TRCTL enabled)
Grouser breaks	2	1
TRCTL drive faults	N/A	1

breaks on the LM wheel occurred prior to nominal use of TRCTL on Curiosity. Additional testing has shown that Curiosity could continue to drive indefinitely on the portion of a wheel that remains when all the grousers on a wheel breaks, if the unconstrained portion of the wheel can be safely shed (Graser et al., 2020).

Overall the wheel health has been improved by several strategic updates: 1) Our science team was able to reinterpret orbital data to predict which terrain types were likely to include the small embedded rocks, enabling the replanning of strategic mobility routes to minimize our interactions with such terrain, 2) The adoption of the new TRCTL control

Figure 52: MAHLI images of the LM wheel from sol 490 (left) and sol 1641 (right). Two grouser are visibly broken in the image from sol 1641. These images provide a good view of the path of the electrical cable to a drive actuator. Image Credit: NASA / JPL-Caltech / MSSS.

strategy to mitigate those times when we must drive on such terrain, and 3) Updating our tactical (daily) assessment of nearby terrain to try to minimize driving over small embedded rocks.

10 Risks to Continued Mobility Success

Curiosity's mobility system has performed admirably during these first seven years, but we are mindful of the potential for future problems. Curiosity has already lost the use of its drill feed actuator, and both the Spirit and Opportunity rovers eventually lost the use of one or more motors during their very-extended missions (Spirit lost use of its RF drive motor, Opportunity its RF steer motor and arm shoulder motor). In this section we describe some of these potential issues and the mitigation strategies we have either adopted already or stand ready to adopt when needed, all of which are summarized in Table 11.

Power Curiosity is powered by a MMRTG, which produces electricity from the decay of plutonium. Over time the MMRTG produces less power, which will limit how far Curiosity can drive per sol and/or how frequently Curiosity can drive during any additional extended missions. Fortunately, power can be accumulated in the onboard batteries so the primary impact will be in longer necessary recharge times, rather than outright loss of capability. Also, future software improvements are planned to increase the VO Full drive speed, which will help enable continued driving while using less power for computing and inertial sensing.

Unsafe Terrain Several layers of mobility fault protection prevent Curiosity from driving on unsafe terrain. On Earth, Strategic mobility planning teams uses Mars Reconnaissance Orbiter (MRO) HiRISE imagery to recommend routes around hazardous terrain, often planning weeks or months ahead, taking science goals into account while keeping the rover safe. MRO altitude ranges from 255 to 320 km; at an altitude of 300 km, the resolution of HiRISE imagery is 0.3 meter/pixel. Tactical RPs plan each sol's drive using a high resolution terrain mesh generated from the NavCam images acquired earlier, usually at the end of the previous drive. The tactical plan may deviate from the strategic plan in order to avoid hazards identified in the higher quality images and terrain mesh. Additionally, the onboad software also guards the rover against entering unsafe terrain by continuously running dozens of reactive safety checks, using VO to keep the rover well localized relative to human-specified keep-in and keep-out zones, and performing traversability analysis to evaluate path safety.

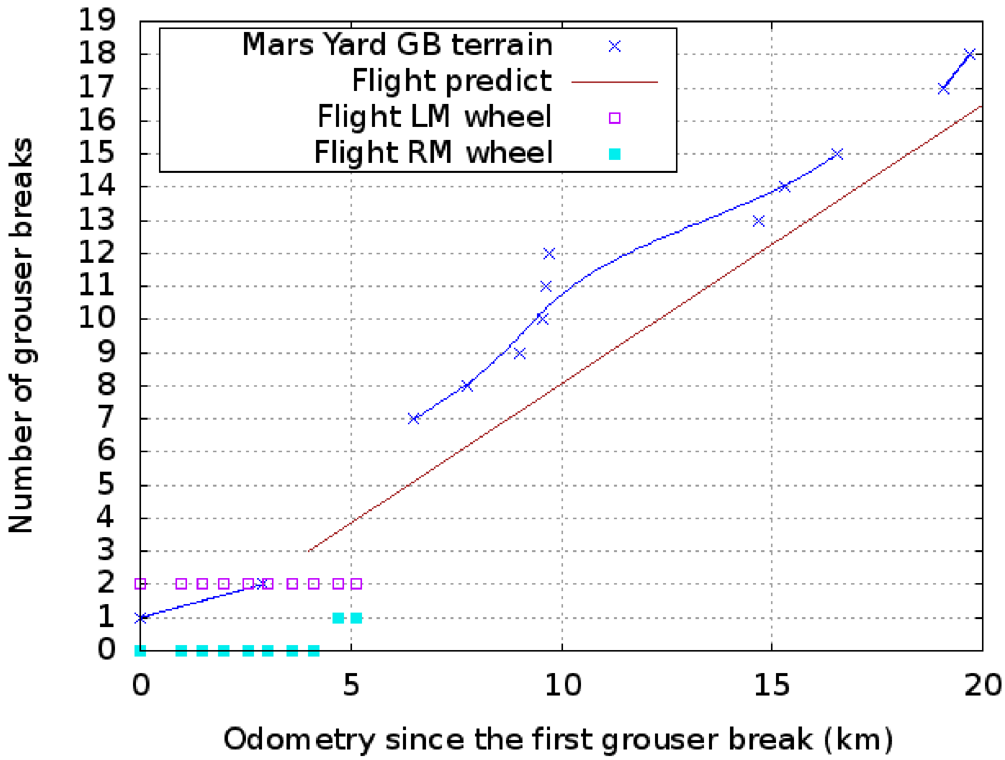

Figure 53: Number of grouser breaks on each wheel, measured since the first grouser break. Thus far, only the left middle and right middle wheels have grouser breaks. GB = good blue terrain, i.e., relatively benign terrain. Given a terrain difficulty assessment of the 5 km of driving since the first grouser break has not been conducted, the lower-than-predicted grouser break rate could be due in part to driving over more benign terrain than predicted.

Permanent Failure of a Mobility Motor or Brake As the age and usage of the drive and steer actuators increase, the risk of an actuator failing to respond to commands increases as well. Opportunity's RF steer actuator stopped responding to commands on sol 433, leaving it permanently toed inward approximately 7°. Mobility was still possible for Opportunity until the end of its mission even though the RF wheel was not steered optimally. Spirit lost its RF drive motor, making that wheel something like an anchor, but driving continued albeit with much less capability. For Curiosity, the ability to turn and drive with a single disabled WSA has been verified on a testbed rover: an MSL wheel backdrives more readily than a MER wheel, as long as its mechanical brake still opens.

Each drive and steer motor has an associated toothed mechanical brake that engages against the motor shaft to prevent motor backdriving when not actively controlled. This prevents, for example, rolling down a hill after a motion command completes. There is no direct sensing that a brake is actually disengaged, though the operations team monitors brake current as an important indicator of brake health. If a brake were to unexpectedly fail to disengage, the corresponding motor would stall, tripping a drive fault as the motor cannot drive through a closed brake. If a drive actuator's mechanical brake were ever deemed to have permanently failed closed, the corresponding motor would be disabled, and that wheel would effectively become an anchor (similar to Spirit), even if its motor were still healthy. However, if a drive motor is disabled but its associated mechanical brake still opens, overall driving should still be better than what Spirit experienced, since the wheel would be backdrivable, turning roughly half as much as the still-functioning wheels (very roughly speaking and depending on the terrain). Mobility would generally be severely compromised if two or more drive motors are disabled, however, even if their mechanical brakes still open.

Camera Failure All of Curiosity's ECAMs are used for onboard hazard detection, and the NavCams are used for VO. If an ECAM should fail, backup pairs do exist, and all have already been used successfully. However, each camera pair is tied to a particular main computer; RCE-A has access to one set of ECAMs, and RCE-B has access to the other set. Switching to backup cameras will therefore require switching RCE computers too. But currently the RCE-A computer is experiencing problems with its NAND flash memory, and although a new flight software version is under development (to shift its file system to use the smaller amount of still-available NOR flash memory), mobility will not initially be supported under that version of flight software on RCE-A. So other options for repurposing cameras would have to be explored in the near term.

Wheel Sinkage Some wheel sinkage is inevitable when driving on sandy terrain. However, if the sinkage continues unchecked, it could lead to wheel embedding. Wheel embedding recovery can require significant effort. For example, when Opportunity encountered a soft sand ripple on sol 446 and high wheel slip and sinkage resulted in embedding, it took more than five weeks to extricate the rover (Maimone et al., 2007a). The MER Spirit rover also experienced wheel embedding at Troy on May 1, 2009, but its 8 month recovery effort was ultimately unsuccessful.

Fortunately, there are several layers of protection for preventing wheel sinkage from continuing unchecked. RPs select drive routes that limit driving through sandy terrain, particularly at high rover tilt angles. VO is performed every drive step in sandy terrain and fault protection will stop the drive as soon as excessive wheel slip is detected. The VO Auto mode also provides additional safety checks even when VO is not active, monitoring overall average current (triggering a VO-enabled slip check when the average wheel motor current increases beyond a parameterized threshold set a bit above the expected current draw for non-embedded driving), turn rate, and other cues that autonomously activate VO and generate slip measurements when needed. This was proven effective during the sol 672 drive, during which VO Auto mode autonomously detected the embedding via the average current check and ran a slip check which then halted the drive, enabling a single sol recovery.

The average current check was first implemented in MER flight software after Opportunity got stuck in the Purgatory ripple, as a filter that only checked readings spanning each single mobility command. It was later refined to its current MSL multiple-command-spanning average current window implementation based on improvements described in (Gonzalez and Iagnemma, 2017).

And while it is true that there is no onboard sensor that directly measures the amount of wheel sinkage, it is monitored in post-drive images by the MSL Operations Mobility subsystem team.

Unknown Conditions Fault protection prevents Curiosity from driving under known unsafe conditions. For example, driving will stop whenever the Surface Attitude, Positioning, and Pointing (SAPP) current attitude knowledge becomes unknown, since that could result in driving off-course onto unsafe terrain. However, while there is always a risk that an unpredictable anomaly or circumstance occurs that results in unsafe driving conditions not identified during flight software development and directly protected against with fault protection, this likelihood is deemed low given our development program, testing, and experience driving on Mars so far.

Wheel Damage The discovery of wheel damage has led to a reduction in the average drive distance. There is concern that once a wheel has the majority of its grousers broken, a shard of wheel skin could reach and cut into the cable running between the MCA and the drive actuator, causing the loss of the ability to command that actuator. We have several layers of protection in slowing the rate of wheel damage and monitoring hazards to the cable. The Strategic Mobility team plans routes to minimize exposure to wheel-damaging terrain. RPs plan drives that limit exposure to nearby small rocks that cause wheel damage. In addition, the use of TRCTL has been shown to reduce the overall wheel damage rate. The current state of wheel damage is monitored in images of the wheels acquired every 500 meters of driving, and initial testing has shown that it is even possible to shed a heavily damaged portion of a wheel that may cause risk to the drive actuator cable.

Wheel Entrapment Wheel entrapment could occur if one or more wheels become trapped on embedded rocks. For example, on sol 2087, the rover was pitched up 18°and made no forward progress because of a steep rock in front of the RR wheel. Fortunately, Curiosity was able to recover on sol 2089 by backtracking 1 meter and taking a different route forward. Several of our operations processes guard against wheel entrapment. On Earth, RPs select routes that limit driving over closely spaced rocks that appear to be embedded; this includes simulating multiple candidate drives over the terrain mesh. Although entrapment is not directly modeled in the simulation, the RPs can visualize wheel placement among rocks and choose a route that stays clear of such dangers. In addition, onboard fault protection modes (e.g., slip checks, wheel current limits) will stop a drive before wheel entrapment.

Figure 54: A 50 cm tall rock with a length of approximately 0.68 meters became wedged between the RF and RM wheels of the MSL Dynamic Test Model rover while driving backward over the rock.

Rock Wedged between Two Wheels Curiosity's passive suspension system is subject to the risk of bad interactions with rocks that could perfectly jam inside it. While the distance between the front and middle wheels depends on the suspension angles, the minimum distance, which occurs when the rover is on a planar surface, is 0.685 meters. The distance between the middle and rear wheels is fixed at 0.575 meters. During mobility validation testing in the JPL Mars Yard with the MSL Dynamic Test Model (DTM) rover, a rock with a length of approximately 0.68 meters became wedged between the RF and RM wheel, and while it did not cause an actuator stall, it did cause tears in the RM wheel skin (Figure 54). If Curiosity encountered a scenario where a rock becomes wedged between a front and middle wheel or a middle and rear wheel, recovery attempts could result in recurrent actuator stalls and additional damage to the already heavily damaged LM, RM, and LF wheels, and may ultimately be unsuccessful.

Although rocks that can cause wheels to become wedged are not directly modeled in simulation, the RPs can visualize wheel placement among rocks and choose a route that stays clear of such dangers. Other mitigations for avoiding such a scenario are the use of keep-in and keep-out zones, AutoNav, and suspension angle fault protection. None of these mitigations were used in the test in Figure 54. AutoNav would have avoided the rock due to its relative height and default suspension limits would have caused the drive to stop prior to the rock becoming wedged between the two wheels. A rock would need to have a height greater than the wheel radius (25 cm) to become wedged between two wheels. During AutoNav with default suspension limits, one scenario where a rock could become wedged between the bogie wheels is if the rock had a width of 0.575 meters and a relative height of 25-33 cm. Because of the mitigations used on Mars and a particular rock width and height is required, this scenario is considered unlikely to occur.

Tip Over Curiosity can withstand an overall static tilt of up to 45°in any direction without tipping over. Should it occur, rover tip over would be a mission ending event. However, given that 1) the rocker-bogie suspension system keeps the rover body relatively level while driving over rocks and undulating terrain, 2) RPs avoid driving in high tilt areas, and 3) fault protection will stop a drive if the maximum expected tilt for any drive is exceeded, the likelihood of rover tip over occurring is very low.

High Centering If a rover drives over a tall, embedded rock and the leading wheels descend into a terrain depression, the rover's belly pan could potentially contact the rock such that the rover cannot make progress in either direction. Such a condition is called high centering. If any of the rover wheels are on sandy terrain, wheel sinkage may occur during recovery efforts, exacerbating the condition.

High centering could also occur during driving on soft terrain, where excessive wheel slip causes progressive wheel sinkage. Although driving over sand ripples can result in slow progress due to significant wheel slippage and excavation, the likelihood of Curiosity becoming stuck from high centering while driving normal to the ripple crest is low, due to the angle of repose of the sand. During a three-day Scarecrow test campaign at Dumont Dunes (Mojave Desert, California) on sand dunes of varying height (up to 2.1 meters), there was no case of high centering that Scarecrow was unable to escape (Heverly et al., 2013).

To minimize the risk of high centering, RPs select routes that avoid driving over tall rocks and sand dunes, and also limit driving through sandy terrain. Onboard capabilities that prevent high-centering include the use of keep-in and keep-out zones to ensure it avoids human-identified hazards even in the presence of slip, and geometric Hazard Detection to detect and avoid such hazards encountered in previously-unseen areas.

Suspension Hardware Failure Mechanical and electrical suspension failures are risks to continued mobility success. On the Scarecrow Testbed rover (Heverly et al., 2013), it was discovered that fasteners on the Side Differential Pivot became loose over time. One possible explanation is that there was no evidence of the expected thread locking compound on the fasteners. Curiosity's CDP has a similar close-out plate and is secured with 16 fasteners. But Curiosity assembly records have confirmed that proper torque levels and thread locking features were used. Still, even though the likelihood of the CDP fasteners coming loose is low, Curiosity's CDP is imaged annually and fasteners are inspected for changes.

If a suspension resolver fails in such a way that we do not even want it powered on, that resolver can be disabled by setting a parameter. However, driving is not allowed with a disabled suspension resolver in the current version of flight software (R12). So a flight software update is currently under development that includes a fix to enable driving while a suspension resolver is disabled. TRCTL uses suspension resolver and IMU data to estimate the contact angle of each wheel with the terrain. Therefore, TRCTL would also have to be disabled if a suspension resolver were disabled.

Mobility Heater or Thermometer Failure Actuators contain wet lubricants that ideally achieve a temperature above -55°Celsius prior to actuation. There are Platinum Resistance Thermometers (PRTs) on each mobility actuator and closed-loop mobility heating is performed for all drive actuators based on a single drive PRT, and for all steer actuators based on a single steer PRT. PRT data for each mobility actuator are recorded in downlink telemetry for the periods when the prime RCE is powered, and at low rates while the rover is asleep. The operations team relies on temperature models to predict the duration of pre-heating needed for scheduling a drive.

Curiosity has two mobility heater circuits. If the prime mobility heater circuit were no longer functional, the operations team would need to command a swap from the prime Power and Analog Module (PAM) to the backup PAM to enable use of the backup mobility heater circuit. However, if both the prime and backup mobility heater circuits are no longer functional, there are three potential options for continuing mobility during extended mission:

1. The operations team could schedule driving only during periods when the temperature models predict the mobility actuators are at a safe temperature without heating, or,
2. Change actuator temperature fault protection limits, drive with the actuators cold, and accept the risks, or,
3. Prior to driving, attempt to use the mobility actuators in a way that generates heat without motion to pre-heat the mobility actuators.

All three options would result in shorter drive times. A risk assessment would need to be performed for the second option and a test campaign would need to be performed to determine the feasibility of the third option. If one of the two mobility PRTs used for closed-loop control is no longer functional, separate PRTs located on other mobility actuators

Table 11: Summary of mobility risks and mitigation. Risks are listed from high to low likelihood of occurrence.

Risks to Mobility	**Worst Case Impact**	**Likelihood**	**Mitigations**
Power reduction may limit drive time	Medium	High	Future software improvements are planned to increase the VO Full drive rate, the drive frequency can be adjusted
Rover driving on unsafe terrain	High	Medium	Strategic route planning, tactical RP route selection, AutoNav, keep-in and keep-out zones, fault protection
Drive or steer actuator hardware failure	Medium	Medium	Ability to turn and drive with a single disabled WSA has been verified
RCE or ECAM failure	High	Medium	Switch to backup RCE/ECAMs. However, due to failing NAND on backup RCE, mobility is not currently supported with file system moved to NOR.
Wheel sinkage can lead to embedding (e.g., MER Spirit)	High	Medium	Wheel slip fault protection, VO Auto, tactical RP route selection, post-drive assessment of wheel images
Rover driving under an unknown unsafe condition	High	Low	Fault protection
Wheel damage may limit driving. A shard of wheel skin may cut into a drive actuator cable, causing the actuator to be unusable	High	Low	Tactical RP route selection. TRCTL has reduced overall wheel wear. Continue to assess wheel damage every 500 meters. Once most grousers on a wheel are broken, consider shedding inner portion.
Wheel entrapment	High	Low	Fault protection, tactical RP route selection, simulation of candidate drives (during planning and fault recovery).
Rock wedged between two wheels	High	Low	Tactical RP route selection, AutoNav, keep-in and keep-out zones, fault protection
Rover tip over	High	Low	Rocker-Bogie suspension keeps rover body relatively level when driving over rocks. Fault protection limits rover tilt.
Rover high centering	High	Low	Strategic route planning, tactical RP route selection, AutoNav, wheel slip fault protection.
Suspension hardware failure	High	Low	Annual inspection of CDP. Future software update will include a fix to enable driving with a disabled suspension resolver. However, TRCTL is not available with a disabled suspension resolver.
Mobility heater or PRT failure may limit drive time	High	Low	Swap to the backup PAM to use the backup mobility heater circuit and different drive and steer PRTs.
IMU hardware failure	Medium	Low	VO can be used to update rover position and attitude, but there will be additional mobility impacts (e.g., increased uncertainty) that will require significant changes to how drives are planned.
Loss of NavCam calibration (affects VO and AutoNav) or HazCam calibration (affects AutoNav)	Medium	Low	Update/upload camera model parameters (unless mount is loose, allowing camera motion)

could be used, and in the worst case the operations team could command a swap to the backup PAM, allowing B-side mobility PRTs to be used for control. A software fix would be required to allow B-side PRTs to be used for closed-loop control while keeping the A-side PAM prime, but would allow driving to continue.

IMU Failure VO is currently configured to update only the rover position, while IMU sensors provide rover attitude real-time updates and undergo bias-removing recalibrations using the imaging-based Sun detection and accelerometer-based gravity-vector detection. But VO actually generates a full 6-DOF pose estimate internally, so if an IMU hardware failure occurs, VO could be used to also update the rover attitude. However, to operate in that configuration would require significant changes to how drives are planned, due to the increased positional uncertainty that would occur. Instead of 8 Hz attitude confirmation, we would only receive updates once per drive step. And turn-in-place commands would no longer close the loop on rover heading to determine when to stop: without the IMU, turn-in-place would be open loop and could terminate far from the commanded heading, particularly if there is significant wheel slip. In addition, TRCTL would not be available without IMU measurements.

Camera Calibration Curiosity and the MER rovers have relied on Earth-based camera calibration to understand the geometric properties of ECAM lenses during onboard image processing. If an ECAM loses calibration, that could preclude the use of onboard autonomous imaging behaviors such as VO (if it is a NavCam) and Hazard Detection during mobility. For example, after the sol 200 anomaly caused a swap from RCE-A to RCE-B and we were forced to use the backup cameras, it was discovered that RCE-B NavCam stereo disparity was sparser than usual, preventing the use of onboard imaging autonomy. Analysis determined that the RCE-B NavCam camera models had inaccuracies in pointing that varied predictably according to the camera temperature. To mitigate that issue, new camera models were generated for each degree between -60 to +20°C and sent to the rover, along with new software and control sequences that updated the system to choose the appropriate model dynamically, based on the current camera temperature. The new strategy restored VO, Guarded, and AutoNav driving modes to the operations team for use on RCE-B starting on sol 335, and that strategy was later built directly into the next version of FSW (R11). In the future, if a physical disturbance happens to an ECAM, or an ECAM mount comes loose, sensor recalibration may also become necessary, and has already been shown to be feasible.

11 Summary

In this paper, we reviewed the performance of Curiosity's mobility subsystem and the challenges of operating it during the first seven years of its surface mission in Gale Crater. We reviewed the mobility modes of operation, described the current condition of the mobility hardware, and gave detailed breakdowns of all of Curiosity's drive failures, including descriptions of the rover's fault protection processes that triggered them.

At the seven year mark, Curiosity's total cumulative odometry was 21,318.5 meters, exceeding the design goal of 20 km. Curiosity has attempted 738 planned drives; 622 (84.3%) successfully completed with the rover arriving at the goal position and 116 (15.7%) did not run to completion. There are 24 types of fault protection that caused the 116 drives to stop early. Sixteen types of fault protection were mobility related and caused 63 of the drive faults. Eight types of fault protection were not mobility related and caused 53 of the drive faults. Of the 116 drives that did not run to completion, 29 drive faults were expected and 87 were unexpected. Despite 15.7% of the attempted drives not running to completion, 91.7% of the planned odometry for the attempted drives was achieved. The 8.3% reduction in odometry has been an acceptable cost, given the benefits of preserving the mobility subsystem.

Comparing Curiosity and Opportunity odometry and elevation after seven years (on each mission's sol 2488), Curiosity has driven 5.34 km less than Opportunity, but has climbed 277.3 meters higher in elevation. Although the odometry and elevation comparisons between Curiosity and Opportunity are of historic interest, mobility choices are guided by each mission's long term strategic science plan and are subject to changes due to near term science objectives and engineering constraints arising from terrain features not evident when planning from orbital images.

Since the use of TRCTL was approved for nominal use on sol 1678, there has been an overall reduction in the wheel damage rate. In addition, the grouser break rate continues to be lower than the predicted rate. Although a significant percentage of wheel skin is cracked on the middle and left front wheel, and there are two grouser breaks on the LM wheel and one on the RM wheel, the current expectation is power will become a limiting factor to driving before wheel damage does. Although drive actuators have exceeded 1x Qualified Life of 15,000 revolutions, a WSA was tested to 2x Qualified Life at JPL, disassembled, and inspected and no failure was observed.

We have summarized the known risks to continued mobility success and their mitigations. The risks to mobility that have the highest likelihood of occurrence are a reduction in available power that may limit the time available for driving, Curiosity driving on unsafe terrain, a drive or steer actuator failure, an RCE-B failure, and progressive wheel sinkage which can lead to wheel embedding. Curiosity has already driven on unsafe terrain (which caused wheel damage) and has already experienced transient RCE failures. An actuator failure and wheel embedding has occurred on MER. Key mitigations to these events include selecting cautious strategic and tactical routes, deploying suitable keep-in and keep-out zones on each drive, using AutoNav to safely explore unknown terrain, employing multiple wheel slip fault protection capabilities, rigorously monitoring wheel sinkage, and integrating future software improvements to increase the VO Full drive rate.

Mars remains a harsh operational environment. The MSL Mobility subsystem team will continue to monitor Curiosity's progress and develop ground support tools, anomaly diagnostics, recovery strategies, and flight software improvements as we continue to explore as-yet-unseen terrains while summiting the slopes of Mount Sharp.

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