

**ROVING ON THE EDGE: ROBOTIC OPERATIONS POWER
PERSEVERANCE'S ASCENT OF JEZERO CRATER RIM**

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Between September 2024 and December 2025 (Sols 1267 and 1720), NASA's Perseverance Mars rover undertook a demanding robotic campaign to ascend and explore the Jezero Crater rim and begin traversing the terrain beyond. Key robotic operation advances included enhanced mobility capability that allowed the rover to navigate fractured, steep slopes with increased tilt and slip tolerances while minimizing wheel motor wear and energy consumption. A flight software update improved capability including autonomous navigation enabling safe and efficient traversal of this challenging terrain. The paper discusses challenges encountered and lessons learned as Perseverance reached important geologic targets such as Soroya Ridge and Witch Hazel Hill and collected high-value samples that may contain potential signs of past life. This phase marks a significant operational milestone, demonstrating how integrated robotic innovations expand the mission's reach into complex, previously inaccessible Martian environments.

INTRODUCTION

The Perseverance Mars Rover has mainly been exploring areas inside Jezero Crater since landing on February 18, 2021. However, it recently climbed its way out of Jezero Crater on Martian solar day (sol) 1358 (14 December 2024) to begin exploring areas at the top and outside of the crater rim. Climbing to new terrain and going beyond the rim has necessitated operational updates to accommodate higher slopes, sandier terrain, and more challenging sampling situations.

The Robotic Operations (RO) team has comprised up to 60 engineers who collectively control, analyze, and maintain the Mobility, Manipulation, Sampling, and Mechanism subsystems of the rover. The RO team has risen to meet the above technical challenges and more, including multiple rounds of layoffs and impacts from the fires that devastated communities near NASA's Jet Propulsion Laboratory in January 2025.

Mars exploration brings with it the excitement of navigating and characterizing ever-changing terrain types. The ascent of the Jezero Crater rim marked the first time Perseverance (or any Mars rover) has attempted to climb slopes greater than 20 degrees using autonomous navigation.¹ The western edge of the crater demonstrating the elevation change associated with the crater rim is

shown on the right side of Figure 1. Improvement strategies planned by the operations team during difficult operations in complex terrain earlier in the mission² were put to good use during 2025, and were made even more effective over time thanks to operational procedure updates.

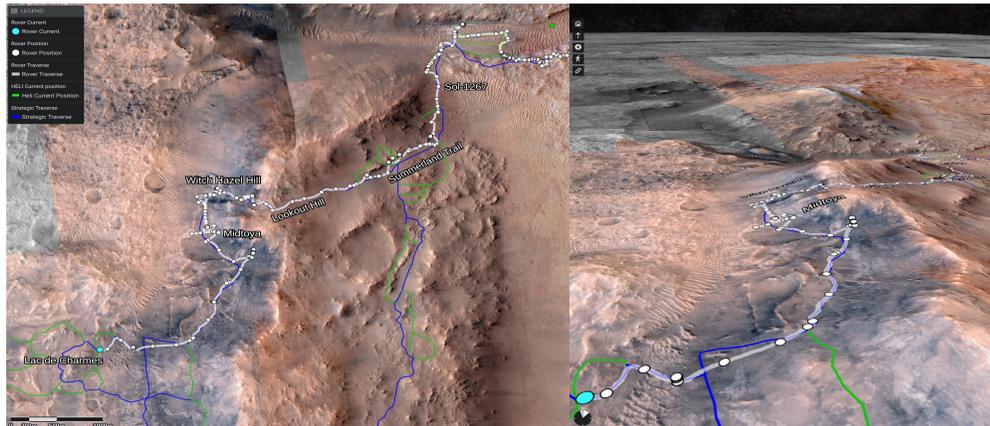


Figure 1 Illustration of the rover's path from sol 1100 - 1720. The left side is an overhead view, the right side is a perspective view of the same area. North points upward in both views. The light blue dot on the left shows the rover's location outside the crater rim on sol 1720 (21 December, 2025).

MOBILITY

Perseverance mobility has demonstrated remarkable improvements over past rovers. As of sol 1710 (11 December 2025) Perseverance has commanded over 42.3 km of driving, taking great advantage of its onboard autonomous driving capabilities like Autonomous Hazard Detection and Avoidance¹ and Visual Odometry^{3,4} (Figures 2 and 3). Over 90% of all driving has been done autonomously, and over 99% has used Visual Odometry to measure its actual position and estimate slip as it drives across the surface (Table 1).

Setting New Mobility Records Perseverance has now driven a greater distance on Mars than Curiosity. The sol 1519 (May 28, 2025) drive of 150 meters on the Mars 2020 mission gave Perseverance the lead in accumulated commanded odometry distance, 36,945 meters for Perseverance compared to 36,859 meters for Curiosity as of its sol 4554 (May 28, 2025). Perseverance also achieved this milestone three times faster than Curiosity (see Figure 4). This can be attributed in part to the enhanced computing capability on Mars 2020 that has enabled 90% of all driving to be done autonomously: a second RAD750 CPU with an FPGA-powered co-processor that accelerates the image processing that underlies Visual Odometry and the binocular stereo-ranging that underlies onboard hazard detection.⁵ And also to a mission operations strategy that allows long drives between sampling sites of interest. The Opportunity rover still holds the longest distance record of 45,161.04 meters (more than even the Apollo-era human-driven lunar rovers), at least for now.

On sol 1540 (19 June 2025), Perseverance drove 411.7 meters. That set a new record for distance driven in a single sol, breaking the previous record of 347.7 meters set by Perseverance

on sol 753 (2 April 2023).^{1,6} Prior to Mars 2020, the Opportunity Mars rover held the record for nearly two decades, 219 meters driven on sol 410 (20 March 2005). Perseverance has now exceeded Opportunity’s one-sol record on 37 different sols as of sol 1601 (21 August 2025).

The long drive was made possible by the dedicated efforts of operations team, which ensured the drive could start as quickly as possible (once the motors were sufficiently warm), and continue as late as possible by accounting for the local tilt of the terrain to keep the Sun out of its cameras’ field of view. The team was also able to ensure the mid-drive attitude update (which incorporates Solar azimuth and elevation) took place long enough after noon that it would not have to pause until the Sun got low enough for the attitude update to succeed. On sol 1540 Mapping and VO were performed during the entire drive, and 403 of 411 meters were driven autonomously i.e., 98% of the driving used AVOID_ALL mode that sol (Table 1).

Table 1 Summary of all drive distance through sol 1710 broken down by Drive Mode. AVOID_ALL is the standard Autonomous driving mode, wherein the rover uses its onboard terrain map to avoid both geometric hazards detected by stereo vision and Keepout Zones specified in advance by human Rover Planners. GUARDED mode performs the same onboard VO and terrain assessment as AVOID_ALL, but will stop when there is an obstacle in the path rather than autonomously avoiding it. AVOID_KOZ only avoids keepout zones, and has not yet been used. UNGUARDED just follows the path sent from Earth directly, ignoring whatever image processing was enabled onboard. See Figures 2 and 3 for visualizations of how these values have grown over time.

Mode	Distance [m]	Duration [hr]	Effective Rate [m / hr]	Total Odom %	Max Distance	
					Sol	[m]
GUARDED	257.05	2.81	91.32	0.61	1292	39.00
AVOID_ALL	31,857.00	343.76	92.67	75.28	1540	403.00
AVOID_KOZ	0.00	0.00	0.00	0.0	-	-
UNGUARDED	9,910.53	120.20	82.45	23.42	1288	93.32

Going More Than the Distance Perseverance was originally designed to travel up to 20 km for its Primary Mission. So its mobility hardware was tested and validated with that goal in mind, its motors having been tested to 2× lifetime (40 km). But we have already traveled more than that distance on Mars, and yet have also recently been tasked with continuing operations for more than an additional decade to support a future Sample Return effort. So RO helped support the effort to re-qualify the rover for an extended lifetime, up to 100 km of total travel (Figure 5).

That validation effort succeeded: all the mobility motors were re-tested and validated to 1.5× this new lifetime (150 km).⁶ The effort also discovered that the mobility brakes were being used

much more in flight than originally modeled, which led to some operational changes described below.

MOBILITY CHALLENGES

Slip Issues

From sol 1283 - 1305 (28 September - 21 October 2025), we began our ascent of the crater rim by driving up Summerland Trail on an initially 15-20° steep hill. During the strategic route planning process the team had initially considered the region to be simple to traverse based on its moderate steepness and benign visual appearance which greatly resembled regolith traverses by both

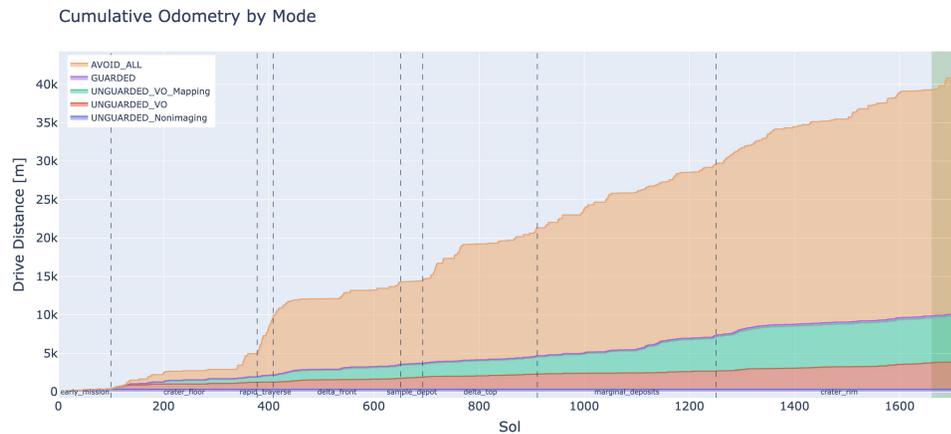


Figure 2 Cumulative plot of Perseverance Mobility Odometry, labeled by drive mode. Onboard terrain analysis is performed in the AVOID ALL, GUARDED and MAPPING modes. The rightmost column corresponds to the Distance data in Table 1.

Perseverance and Curiosity in the past. However, the terrain proved far less cohesive than anticipated, providing very little traction for the rovers' wheels. The tilt combined with the high slip terrain resulted in numerous drives faulting out, even with higher slip limits in place. Rover planners identified that the northern side of the hill, where rocks were peeking out, could potentially be less slippery than the middle route that was originally planned. Alternative driving methods such as cross-slope, backwards, and even cross-slope backwards driving were done to mitigate slip and get the rover to that less slippery terrain, which eventually allowed the rover to ascend to the top of Summerland Trail.¹

Summerland Trail marked the first use of "Slip Tables" during the surface mission to allow full use of autonomous navigation with higher slip limits (above 50% slip) in place.² Widened yaw checks were also used during directed driving as the rover experienced high amounts of yaw slip during cross-slope driving in the loose terrain.

Following the ascent up Summerland Trail, the rover’s steer actuators experienced a number of CMAX_SLOW faults caused by high motor current readings that persisted across multiple adjacent 64 Hz samples. The terrain was still benign at the time and there was no indication of significant wheel interaction with the terrain, something typically seen with high current events or motor stalls. Additional investigation determined that these events were an unintended side effect of parameter updates that were made to prevent “hardbrake” fault responses, in which the brakes are stopped immediately rather than being given time to ramp down slowly. Motor control software was no longer monitoring encoder motion after the motors were released by the Rover Motor Controller Assembly (RMCA), resulting in poor motor commutation. A flight parameter adjustment was made to increase that monitoring time to 120 seconds, accounting for idle time and resolving that issue. Enabling Early Dynamic Braking also contributes to a reduction in CMAX_SLOW events at the start of actuator use, as explained below.

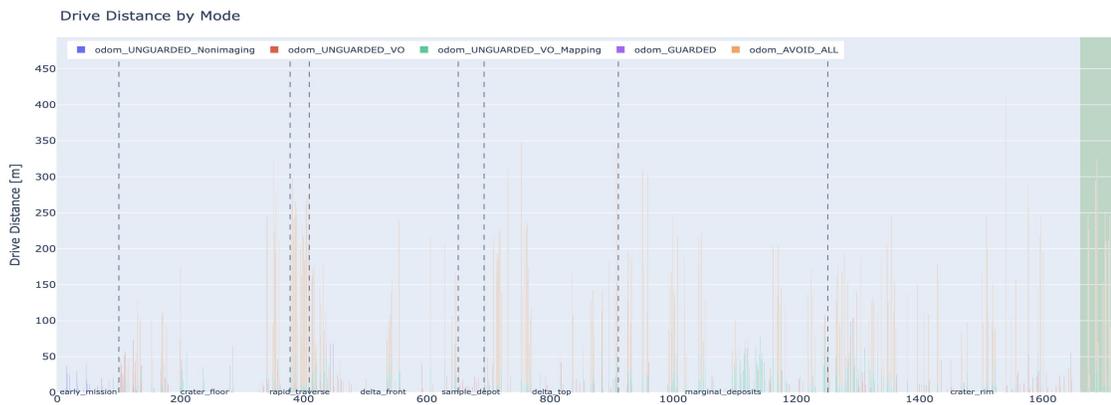


Figure 3 Daily plot of Perseverance Mobility Odometry, labeled by drive mode. Onboard terrain analysis is performed in the AVOID ALL, GUARDED and MAPPING modes.

Featureless Terrain Impact on VO

One final climb brought the rover up to Lookout Hill, marking the highest elevation of the mission. Rover slip returned to manageable values but there was a 75m stretch of terrain over the course of 3 drives (Sols 1339, 1342, and 1347, 25 November - 3 December 2024) which was so visually bland (Figure 6) that our Visual Odometry (VO) algorithm regularly failed to identify and track terrain features, causing drive faults on the first two sols. Over the course of the M2020 mission, VO has had a 99.83% success rate. This short stretch of terrain accounted for 34 VO failures, 42% of all failures seen during the mission as of sol 1710 (11 December 2025).

For the sol 1347 (3 December 2024) drive, Rover Planners disabled the standard VO failures fault protection and manually sequenced a “slip check” strategy, requiring VO to run successfully only once every 20 meters. This was based on mechanical design specifications which state that the rover is still capable of extricating itself even after 20m of motion without forward progress. The terrain over these sols had proved to be firm with low chance of embedding which provided extra confidence. VO failures continued over the first 26m of the Sol 1347 drive, at which point the rover reached more visually interesting terrain and VO performance returned to nominal.

Mobility Mechanism Issues

The mobility system has performed well on the western side of the Crater Rim. The major exception was our inability to reach a region of bedrock of scientific interest at Midtoya. The terrain in that area proved very sandy and while more rocks were present than in Summerland Trail, they were small and loose. The rover experienced slip in excess of 94% on slopes of around 20°, so the Science team chose to move on to other areas.

During this period, Early Dynamic Braking (EDB) was introduced to reduce wear on the brakes at the beginning of drives. The rover uses toothed brakes on the drive and steer actuators, and some motor movement can occur between the brake teeth overnight. To account for this potential motion, the motor field positions are not tracked during rover sleep cycles. Instead, they must be determined prior to the first use of each motor during startup mode. However, this must be done

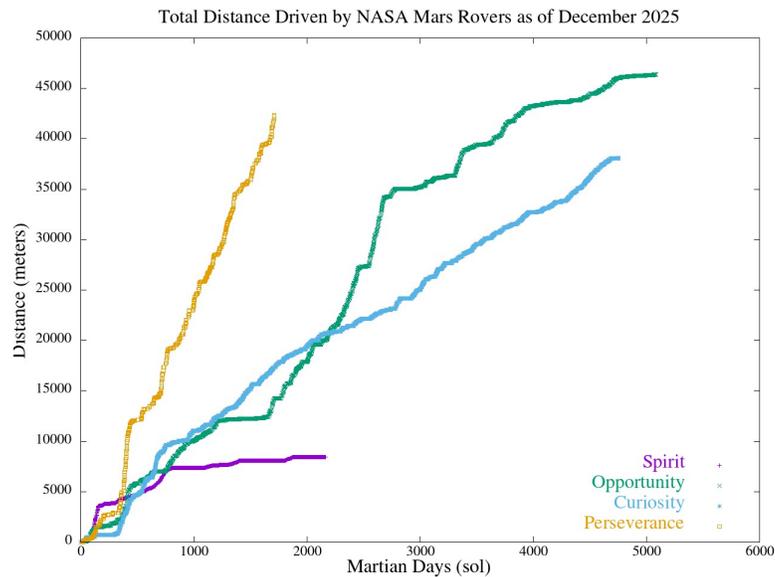


Figure 4 Daily plot of Spirit, Opportunity, Curiosity and Perseverance Mobility Odometry commanded distance as of December 12, 2025. Curiosity and Perseverance are both still driving across the Martian surface. The Sojourner rover's 83-sol mission drove 104 meters in total, and is not shown here.

after the brakes are released because the motors may move during the procedure, so a fixed commutation state is applied as the brakes are disengaged. Since the motors may have moved while the rover was asleep, this commutation state may be incorrect and apply a random rotation to the motors while the brakes are still engaged, resulting in face-to-face disengagements and scraping that can damage the brakes.

To reduce this brake wear, EDB was introduced at the beginning of the first mobility activity on each wakeup cycle. Dynamic braking is a mode where no power is applied and the motor is shorted, allowing back EMF to create torque in the opposite direction of motion. It is already used during braking to help slow the motor if it has not already stopped. EDB applies this same mode while the brakes are being released. With no external load, this holds the motors stationary,

reducing the risk of scraping. Once the brakes have disengaged, the motor transitions to startup mode to find the correct field positions and begin commutating to move the motor.

EDB is only needed on the first mobility motion after the rover wakes, as there is less risk of the motors moving between daytime drives. Additionally, if there is some external force driving the wheels, such as a wheel resting on a rock or a steep incline, we would not want to do EDB as the external force might overcome friction and cause the motor to move. Thus, it is safer to do it at the beginning of a sol, when the rover is parked in a safe position from the end of the previous sol.

To enable EDB on only the first mobility motion, a sequence of commands was developed to enable EDB, make a small motion that uses all mobility actuators (either turning in place or driving



Figure 5 Overall Strategic Drive Route. Points in white indicate where the rover was at the end of each sol. Perseverance landed near the easternmost point in the white drive path, and is currently located at the light blue dot at the westernmost point. Paths in dark blue are the proposed route for future exploration, including a potential return back to the Delta area near the original landing site. Driving back into Jezero Crater Delta along this route will require the mobility system to traverse a total distance of up to 100 km.

straight a short distance, depending on initial wheel pointing), then disable EDB after the actuators complete startup mode. During EDB testing we learned that there is a delay after commanding the brakes to disengage before voltage is applied to the motors, allowing the brakes to be released with less risk of damage. This new sequencing was tested in flight on sol 1615 (September 4, 2025) and has continued to be used with mobility activities since then.

GLOBAL LOCALIZATION

RO has been working toward giving Perseverance the ability to re-localize itself against orbital maps. This capability, known as global localization, has been in development for several years,^{7,8} and will enable the rover to reduce its position uncertainty and complete drive longer, kilometer scale distances in a single plan. The capability is enabled by a commercial Snapdragon CPU that was added to the rover alongside its radiation-hardened primary compute elements as part of the Helicopter Base Station (HBS). The Snapdragon provides more than a 20× speedup over the

RAD750 primary computers, enabling high-compute image processing algorithms to complete in minutes rather than hours. Unfortunately, because the RAM does not have ECC and is not radiation hardened, its RAM has begun to exhibit both permanent and intermittent problems.

During 2025, we studied the Snapdragon's RAM to characterize its behavior and have implemented solutions to work around the faulty memory.⁹ The problem first manifested as tiny, <1 mm scale differences in the position results between multiple runs with identical input data. We then ran a newly developed memory testing activity that discovered at least 46 weak bits in the Snapdragon's 2 GB RAM, which are RAM memory cells that cannot reliably hold a '1' state and randomly flip to a '0' within seconds. We also observed a correlation between higher temperatures and an increase in bit flips among the weak bits. To work around the faulty memory, we developed new software to quarantine memory pages of known weak bits to reduce the chance of a weak bit corrupting the global localization program. In November 2025 on sols 1686 and 1693, we successfully ran the global localization program with the new memory quarantine software and detected no memory corruption in the results across multiple runs.



Figure 6 A featureless Navigation Camera image taken during the Sol-1342 drive, which faulted after experiencing 21 VO failures to converge over 50 meters of driving.

In addition to the memory quarantining mentioned above, we also run the same process more than once and compare the final localized answers. In our original design those answers had to match exactly, but we have added a new thresholding step to allow for the possibility that new weak bits might be discovered at execution time. Even if two localization answers differ, we will consider them to match so long as the 2D and 3D distances between relocalized positions, and the overall uncertainty estimate, agree to within certain parameterized thresholds, nominally 10 cm.

As a sneak peak beyond the reporting period covered by this paper in general, we successfully ran the full Global Localization activity on sol 1762 (2 February, 2026). In December 2025 we had uplinked an orbital (HiRISE instrument) map covering a square mile area of the Lac de Charmes region outside the Jezero Crater rim at 50cm resolution (Figure 7). At the end of a 159 meter autonomous drive in the NE corner of that region on sol 1762, five pairs of NavCam stereo images were collected and orthographically reprojected into an overhead view, and localized against this map using the Censible algorithm on the HBS.⁸ The first attempt to localize failed due a memory

checksum issue early in the process, but the next two attempts ran to completion with identical and valid results. Because the final two attempts agreed to within the required tolerance, the answer was accepted and merged into the onboard position and uncertainty estimates. *This marks the first time a non-radiation-hardened co-processor was used as part of a NASA Mars rover onboard safety assessment.*⁹

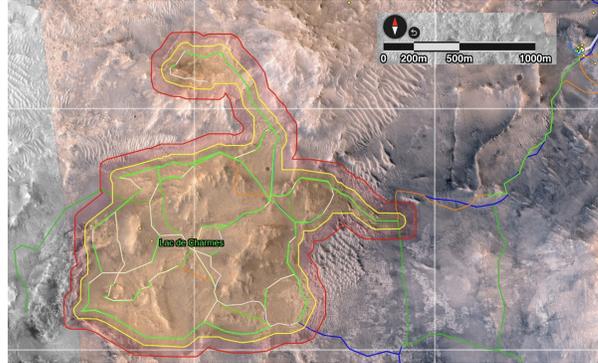


Figure 7 The Lac De Charmes area outside Jezero Crater, a region we intend to explore throughout the first half of 2026. The colorized area shows the approximately 1 square km of map data that was uploaded to Perseverance in preparation for running Global Localization anywhere throughout the region. The uploaded map has 50×50 cm² resolution per pixel.

A similarly successful test was run on sol 1775 (16 February, 2026). In this case only two runs were needed as no new memory errors appeared, and the results of both runs were identical.⁹

ROBOTIC ARM

Facility Contact Sensor Learns New Tricks Shortly before collection of the Green Gardens core on sol 1420 (16 February 2025), the Scanning Habitable Environments with Raman and Luminescence for Organics and Chemicals (SHERLOC) instrument team expressed interest in performing spectroscopy measurements on the cuttings generated by the coring process. The idea was to be able to access material below the standard abrasion depth, potentially enabling measurement of material less altered by radiation. This request presented several engineering challenges for safe and effective placement of the SHERLOC instrument. These challenges were largely the result of the relatively extreme surface geometries created during coring, combined with tight SHERLOC placement requirements. The coring operation creates a 27 mm diameter borehole often more than 60 mm in depth. This borehole is usually surrounded by a cone of cuttings that is often around 30 mm in height. See Figure 8 for the results of the Green Gardens coring operation.

The SHERLOC placement must be accurate both laterally and along the normal direction. Lateral accuracy must be sufficient to make sure the cuttings to be observed will be within the SHERLOC

field of view. Accuracy requirements along the normal were made more challenging by the sol 1024 (6 January 2024) SHERLOC focus mechanism failure resulting in SHERLOC becoming a fixed focus instrument. Therefore, the only method of focusing the instrument is to use the arm to place the instrument closer or further from the surface. To add to the challenge, the SHERLOC depth of

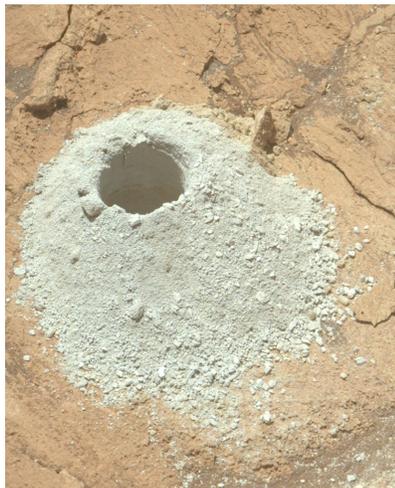


Figure 8 Green Gardens coring borehole and cuttings. Credit NASA/JPL/Malin Space Science Systems.

field is fairly unforgiving at around ± 0.5 mm. This means the arm must be placed within this margin of error along the target normal to achieve in focus measurements. It also means the surface being observed must be flat and normal to the instrument boresight for the entirety of the observation to be in focus.

Given the natural geometry of the cuttings pile, the only real option for placement would be to target a side of the cuttings cone. As the cuttings form roughly a cone, the surface is constantly curving which is less than ideal from a flatness perspective or for being able to approach at the appropriate normal vector given lateral arm placement uncertainty. The side of the cuttings cone is also sloped dramatically differently than the surrounding terrain. Placing the arm normal to the cuttings would often result in terrain collisions with other parts of the very large Mars 2020 turret.

Enter the facility contact sensor (FCS). This piece of hardware was designed to be used to reduce arm placement uncertainty along the normal direction. It consists of a roughly 78 mm diameter plate attached to a pair of redundant contact switches. Moving the FCS toward the surface until the switches trip enables the surface location to be better estimated. Given the FCS geometry, we realized it could also make an excellent tool for flattening out cuttings piles. On sol 1424 (20 February 2025), the first ever FCS touches on drill cuttings were performed. Two FCS touches were commanded. The first was centered on the borehole itself and the second offset about 30 mm in the downslope direction, toward the largest prevalence of cuttings. After the touches, an image of the FCS was taken to inspect for cuttings adhesion. Figure 9 reveals a variety of small spots of cuttings on the FCS plate.

These touches greatly improved the cuttings geometry for SHERLOC placement, generating a relatively flat surface with a normal consistent with the surrounding terrain. WATSON imaging

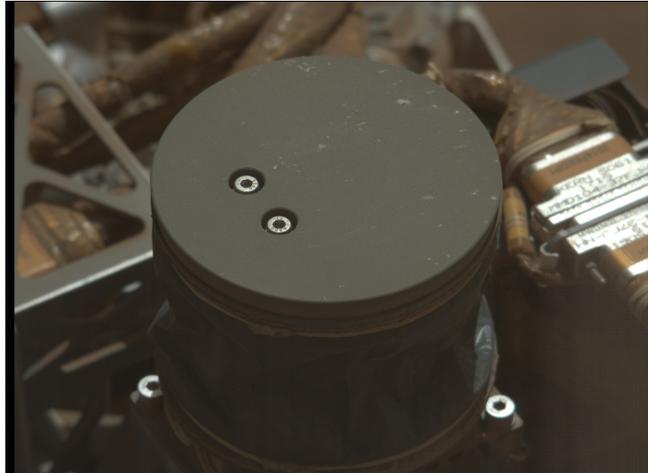


Figure 9 Facility contact sensor inspection after flattening the core cuttings pile. A small amount of cuttings are present on the plate. Credit NASA/JPL/Malin Space Science Systems.

was captured after the FCS touches and was used to select the target for SHERLOC placement. This enabled reducing the lateral placement uncertainty from 27.8 mm when selecting directly from engineering camera stereo data, down to 5.4 mm by using those WATSON images. This reduction in lateral placement uncertainty was critical for ensuring that the SHERLOC observation did not end up over the borehole or outside the flattened cuttings area. Onboard the rover, immediately before placing SHERLOC, WATSON autofocus was used to estimate range to the surface. SHERLOC was placed relative to this estimate in order have the best chance possible of an in-focus SHERLOC measurement. To avoid any portion of the borehole ending up in the WATSON autofocus subframe (potentially resulting in inaccurate range measurements to the top of the cuttings), a target selection keepout around the borehole was established. This keepout was 12.7 mm beyond the edge of the borehole to cover arm placement uncertainty plus the size of the WATSON autofocus subframe. Figure 10 shows the 30 cm standoff WATSON image taken after the FCS touches with the target keepout as well as the SHERLOC target selected by the science team. SHERLOC was successfully placed on sol 1426 (22 February 2025) for its first ever core cuttings observation.

Arm Faults For hardware safety, the arm is secured before drives through a sequence of multi-joint and single-joint stowing motions. These motions drive hardware features on the elbow and turret joints into their passive stow restraints on the rover body. On Sol 279 (2 December 2021), a force/torque-sensor (FTS) fault was encountered during unstow where the standard free-space y-axis force (F_y) limit was exceeded by 1 N (halting further arm motion). An investigation revealed that the lateral contact forces during the turret stow / unstow motions are sensitive to rover attitude and temperature, and the default free-space limits had insufficient margin to

accommodate them. To increase headroom, the force limits were subsequently raised to values consistent with the maximum allowable loads designed for all free-space arm poses.

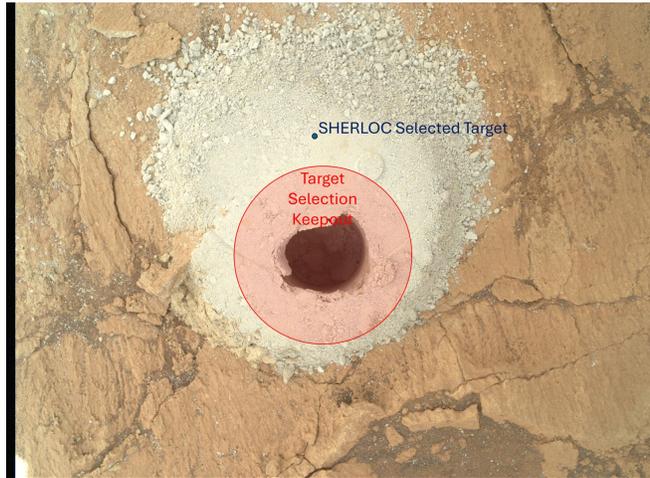


Figure 10 30 cm standoff WATSON image showing the cuttings target selected for observation by SHERLOC as well as the keepout around the borehole in which targets could not be selected, to ensure no overlap with the borehole. Credit NASA/JPL/Malin Space Science Systems.

Despite this workaround, similar faults were again observed on Sols 1235 and 1289 (10 August and 4 October 2024) at the start of the crater rim campaign, and were thought to have been caused by a combination of high rover tilt and cold temperatures. To minimize these nuisance faults, the arm team switched from using pose-agnostic force limits, and instead designed customized stow / unstow limits around a maximum allowable wrench combination specific to the stow pose that still kept all arm links within their structural limits. These revised limits were validated by a prediction profiler that established a correlation between rover pitch, roll, and arm temperature to the stow / unstow loads (Figure 11). There is still a non-zero risk of faulting under a worst-case temperature and attitude combination, but we are far more robust to nuisance faults under this new paradigm.

Arm Force/Torque-Sensor Perseverance Beyond crafting specialized FTS limits for the robotic arm stow / unstow anomaly response, we also perform long-term performance trending and maintenance of the robotic arm's FTS (RA FTS). Trending for the RA FTS residual error (after gravity compensation) during free-space motions at a range of gravity load vectors is shown in Figure 12.

Maintaining a well-calibrated RA FTS allows us to ensure adequate fault protection limits for hardware safety (i.e. sufficient margin to hardware structural limits) during the full range of robotic arm activities on Mars and the capability to perform accurate closed-loop control for robotic arm preload activities (e.g. docking and coring / abrading). To date, we have successfully performed

one in-situ recalibration of the RA FTS on Mars (on Sol 883, 14 August 2023).² This recalibration was motivated by an FTS anomaly on Sol 521² (7 August 2022) and drift observed in the Fz channel during FTS checkout activities around Sol 600 (27 October 2022, see Figure 12). Sensor performance since then has been stable across all force and moment channels, and for both the primary and backup-side sensor. We maintain the capability to perform additional FTS recalibrations in the future using our established process.¹⁰

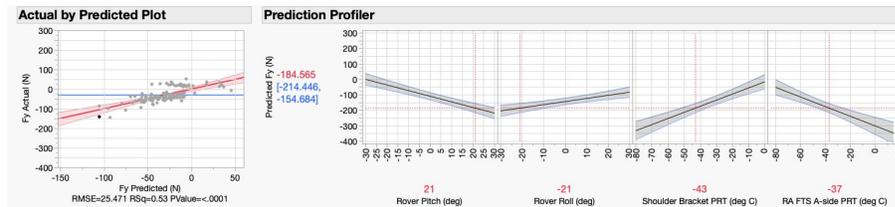


Figure 11 Model fit and prediction profiler developed with JMP using data collected during arm unstows between Sol 17 and Sol 1289 (7 March 2021 - 4 October 2024, inclusive). Profiler shows a predicted Fy range using an example worst-case pitch / roll combination and representative temperature gradients.

SAMPLING

The Sampling and Caching Subsystem (SCS) has successfully acquired rock core, regolith, and atmospheric samples and prepared abraded rock surfaces for proximity science instrument placements dozens of times throughout the mission. The SCS consists of a coring drill mounted on the end of the RA's turret, referred to as the Corer, the gas Dust Removal Tool (gDRT) also mounted on the turret, and the Adaptive Caching Assembly (ACA) located inside the body of the rover as seen in Figure 13. The two Corer stabilizers are preloaded onto rocks during abrading and coring, while the Corer feed translates the bit of a rotary-percussive drill into contact with the rock. The percussion mechanism is critical to the drilling operation, using percussive energy to chisel and chip away at the rock to produce either abraded patches or core samples. After abrading, the gDRT is used to remove dust and rock powder from the abraded patch to clean the surface for instrument observations. As of sol 1720 (21 December 2025), the SCS has created 56 abraded patches, puffed with the gDRT 301 times, and sealed 31 sample tubes: 25 rock core samples, 2 regolith samples, 1 atmospheric sample, and 3 witness tube samples which document the SCS's exposure to the Martian elements over time (see Figure 14 for sample images).¹¹

ABRADING FAULTS

Although SCS operations have seen great success throughout the ascent of the crater rim, a new instance of stabilizer slip occurred while abrading on sol 1456 (24 March 2025). Stabilizer slip occurs when the stabilizer tips suddenly move from their preloaded position on the rock during drilling. The causes of stabilizer slip are many, but most often it is the result of drilling dynamics

between the bit and rock that leads to a sideload on the bit sufficient to overcome the friction between the stabilizer tips and rock. Once the stabilizers begin to move, arm preload is quickly lost resulting in a fault as drill and/or arm force limits are exceeded. While stabilizer slip is rarely a hardware risk, operators would prefer to avoid this halt in drilling which often requires one or more sols of complex recovery activities. For this reason, operators go to great lengths to select targets that are unlikely to result in stabilizer slip through rigorous environmental assessments for pebbles, significant topography, loose regolith, etc. These assessments, however, must be balanced with the Science team's desire for interesting, geologically rich targets, which often leads to suboptimal targets with nonzero stabilizer slip risk.

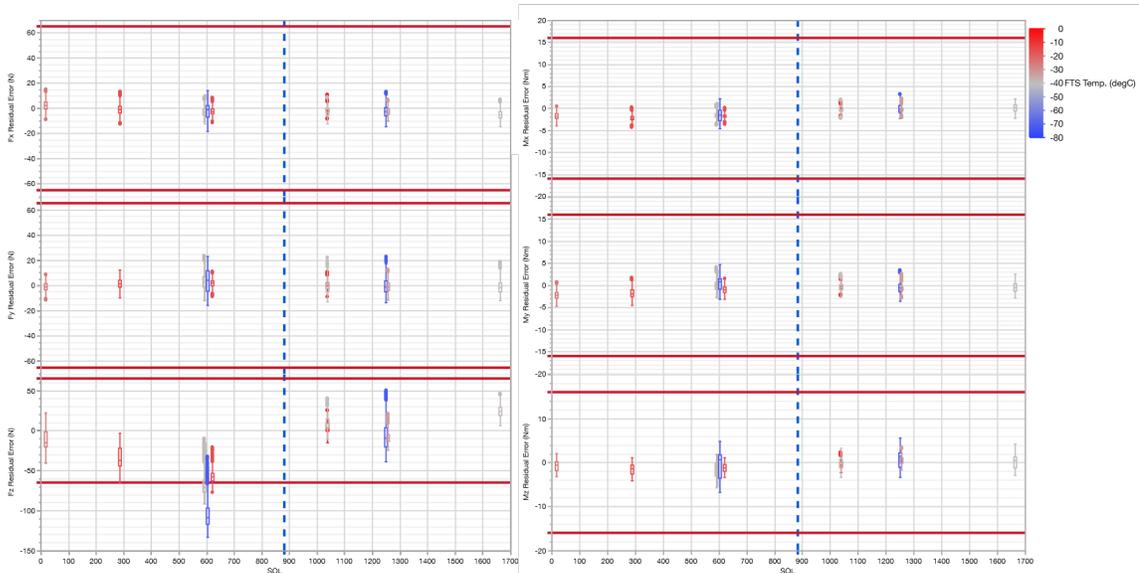


Figure 12 FTS absolute sensor error for primary-side force and moment axes across a comprehensive range of gravity vectors. Collected approx. 2x per Mars year at targeted operating temperatures (color). Horizontal red lines mark sensor error requirements ($\pm 65\text{N}$ / $\pm 16\text{Nm}$); vertical blue line marks sensor recalibration on Sol 883 (14 August 2023).

The sol 1456 abrasion of Great Mountain is a classic example of this behavior and resulted in a 104 N preload loss, as seen in Figure 15. This target was located on a rock with significant topography (see Figure 16) and uplink operators noted bit and stabilizer tip topography that exceeded Corer placement guidelines. Science's significant interest in this rock led the team to press on and accept the stabilizer slip risk. In practice, the topography proved to be insurmountable, and a large slip event early on in the drilling operation prevented the creation of an abrasion patch on this target.

Not all preload loss events tell the same story, though. As seen in Figure 15, while several abrasions exhibited loss of preload, only sol 1456 can be attributed to stabilizer slip. Preload loss

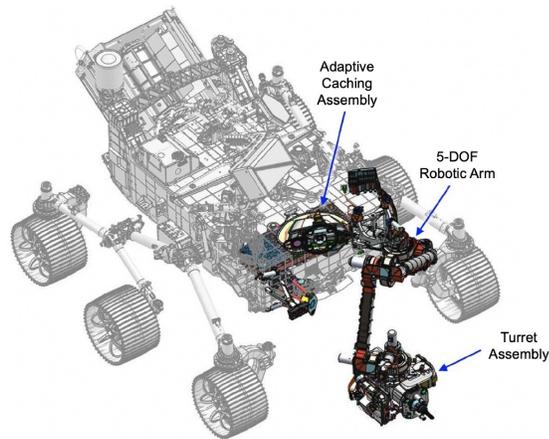


Figure 13 Mars 2020 Rover with SCS components highlighted.

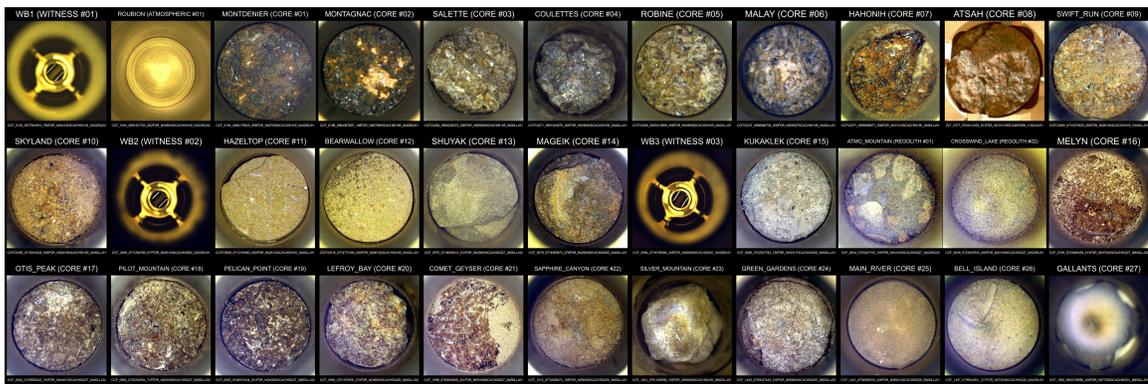


Figure 14 Cachecam or Mastcam-Z images of all 33 acquired (31 sealed) samples in order of acquisition. Credit: J. Maki.

can also be explained by the rock sinking into the surrounding regolith during drilling dynamics, as seen with the successful Pyramiden abrasion on sol 1663 (23 October 2025). More interesting still was the rock slip event during the failed Drakes Point abrasion on sol 1565 (14 July 2025). In this case, the Science team pushed for an abrading attempt on a rather small rock. The RO uplink team deliberated on whether drilling the rock posed a hardware risk as the size and shape of the rock indicated a high likelihood that the rock would rotate during the preload operation, but ultimately determined the target was solely a fault risk. During drilling, the rock began to walk across the workspace eventually triggering an arm force fault due to the loss of preload. The risk proved fruitful, though, as the operation still reached sufficient depth to create an abrasion patch worthy of proximity science (see Figure 17).

FLIGHT SOFTWARE UPDATE

When Perseverance landed, the ENav autonomous driving software¹ was configured to perform a conservative analysis of the terrain. For example, the maximum terrain tilt it was allowed to climb was only 16 degrees, based on the worst-case drive performance of the Curiosity

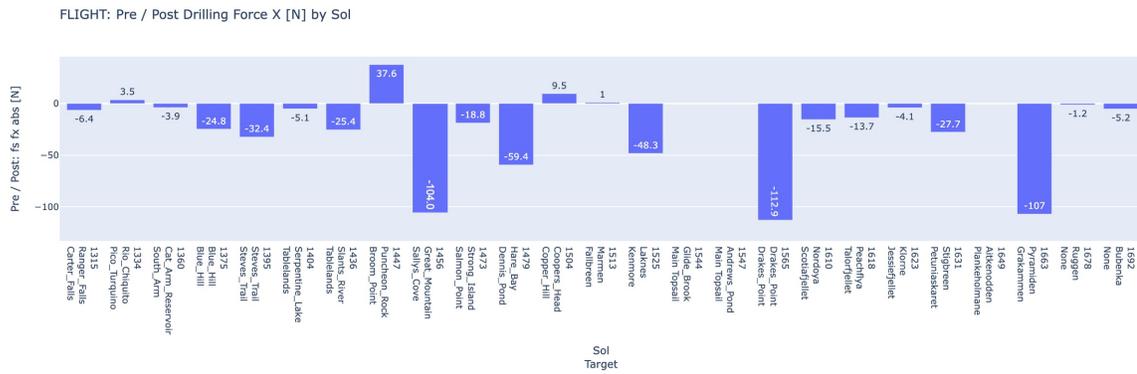


Figure 15 Change in arm preload between the start and end of abrading for all abrasions between sols 1267 and 1720.



Figure 16 A cropped Front Hazcam image of the Corer showing its state after a stabilizer slip event halted the Great Mountain abrasion attempt on sol 1456.

“Scarecrow” rover in pure sand dunes.¹² As it turned out, that conservative limit still enabled nearly all driving on the Jezero Crater floor during the first three years. But during the two months spanning sol 1096 – sol 1159 (March 20 – May 24, 2024), no AutoNav driving was possible due to tilts above 16 degrees and/or greater rock density in a region of complex terrain.¹

A tiger team was formed to reconfigure ENav for more complex terrain, known as the *Autonav Roundtable*. Several strategies were taken: updating command sequences, changing parameterized limits like the maximum allowed tilt (based on Monte Carlo studies proving such changes would not impact the overall performance), and in some cases making updates to the mobility flight software (FSW).¹ In all, 14 mobility-related changes were accepted and implemented (12 related to ENav and 2 to Global Localization), comprising the changes included in the S8.1 version of FSW.

The M2020 FSW is partially segmented into domain-based *components*. A component is a collection of FSW code modules that can be replaced onboard the rover in a limited fashion,

without changing the rest of the FSW. That allows generally faster regression testing, review and deployment of such changes than would be possible with an update that impacts all the FSW.^{13,14} In this case, all the changes were contained within the mobility component, which allowed flight deployment to occur relatively quickly.



Figure 17 A cropped Front Hazcam image of the partial Drakes Point abrasion patch after the rock slipped during drilling on sol 1565.

Perseverance started using the S8.1 Mobility component on Sol 1588 (8 August 2025). The prior FSW version S8.0.0.3 had been in use since Sol 1151 (16 May 2024). However, the high fidelity engineering model of Perseverance known as the Vehicle System Testbed (VSTB) was unfortunately not available to perform all the desired mobility regression Validation and Verification (V&V) tests before that update. Some of its mobility motors had been removed to perform the life-testing mentioned in the *Going More Than the Distance* section above. As a result, some of the changes made could not be approved for use in flight until months later, once the mobility system became usable again and V&V could be completed.

In addition to the S8.1 full software release, we also developed and deployed “hot patches” to fix small issues.¹³ The first was a small fix needed to run Global Localization in the S8.0.0.3 version of FSW, which was later incorporated into the S8.1 component update. Another Global Localization patch became necessary for S8.1 after we decided threshold checks were needed. That hot patch is now part of the Global Localization process in flight until a new S8.1.0.1 mobility component including equivalent behavior is uplinked, an activity currently planned for early 2026.

Another hot patch has been developed to correct a subtle problem tracking odometry on a small subset of motors that use Hall sensors. That patch is also expected to be uplinked in early 2026.

STAFFING CHALLENGES

Operations staffing challenges can occur due to natural attrition, layoffs, budget cuts, and natural disasters. M2020 encountered all four of those during the last year, which contributed to a larger departure rate than in previous years. Overall, 25 RO team members left the team during this reporting period, reducing team size by 53.2%. The departures occurred for a variety of reasons, including staff leaving JPL for an opportunity at another company (7), staff leaving RO for another role at JPL (4), staff returning to school to pursue a higher degree (1), staff impacted by

JPL layoffs (5), staff who left JPL due to a change in the telework policy (4), and staff cuts due to budget cuts (4). The loss included several RO leadership roles, such as the Sampling and Caching Deputy lead, the RO Teamtools Lead, the Robotic Arm Deputy Lead, and the Mechanisms Lead and Deputy Lead. All of these leadership roles have been subsequently filled except for Mechanisms Deputy Lead. Due to FY26 budget cuts, only 40% of the lost RO staff were replaced.

Natural disaster impacts to Operations do not occur frequently, but in January 2025, the Eaton fire devastated neighborhoods close to JPL, becoming the second most destructive wildfire in California history. Coincident with the Eaton Fire, there were multiple other fires in Southern California impacting M2020 staff. On January 8, 2025, JPL was closed (except for emergency personnel) and M2020 Operations was suspended for twelve days. As a result of the fires, when nominal Operations resumed 17.6% of the RO team were still displaced from their homes. It would be months before they could return to their usual number of tactical shifts. Over that period, other RO team members increased their tactical shift count, significantly slowing some RO strategic work. Despite the staffing challenges, this reporting period has been very productive for RO.

LESSONS LEARNED

RO Team Organization Continues to Evolve The RO team was created for M2020, motivated by our experience on earlier missions. Due to the nature of surface exploration, project management decided to give the teams that manage ever-changing terrain interactions some operational independence and a voice at the highest levels of the project. Prior to landing, the roles within RO were Rover Planners, Sampling and Caching, Mobility Downlink, Robotic Arm Downlink, and Helicopter Integration Engineers (HIE). Since landing, one role (Mechanisms) has been transferred to RO, one RO role (HIE) has been disbanded, and a new RO role has been created (RO Teamtools). During the early mission, there was actuator expertise in the Engineering Operations (EO) Mechanisms team and in the RO Mobility, Robotic Arm, and Sampling and Caching teams. At the beginning of FY24, M2020 decided to consolidate actuator expertise within a single team by transferring the Mechanisms team from EO to RO. After Ingenuity ended regular operations on April 16, 2024, the HIE team continued to downlink Ingenuity housekeeping data and surface images, and Ingenuity remained in contact with Perseverance for more than 6 months. Its last successful communication with Perseverance on November 26, 2024, set a record for the distant communication between two vehicles on the surface of Mars (2.96 km). On January 27, 2025, the HIE team was disbanded. During early mission, team tool development was coordinated by each individual RO role. But given there is a toolset in common to all the RO roles for trending, there was a desire to appoint a single RO Teamtools lead who would be effective in preventing disparate effort with contributors from various roles and no clear owner, which would result in inconsistent contributions over time and a growing backlog of bugs and feature requests. In February 2025, the RO Teamtools team was created with a lead and two other developers. The current RO Org chart reflects the addition of the Mechanisms team, the removal of the HIE team, and the addition of the new RO Teamtools team. An additional change under consideration is moving the Robot Sequencing and Visualization Platform (RSVP) team from the Ground Data Systems team to RO.

Risk Posture of FSW Patching is Mission Dependent One of the lessons learned from the Mars Exploration Rover (MER) mission was to expect FSW updates throughout the lifetime of a rover

mission. An FSW update can be a hot patch, a cold patch, or a full release.^{13,14} During the first 10 years of the MSL mission, 13 hot patches were delivered to flight, averaging a new hot patch every 9.2 months. Thus far in the M2020 mission, two hot patches have been delivered to flight, averaging a new hot patch every 30 months. Part of the reason for a significantly lower rate of hot patching on M2020 is a more conservative risk posture among the FSW team and project management, which was driven by a requirement for Perseverance to still be operational to rendezvous with a future Sample Return Lander. Two of the authors of this paper were previously the FSW lead on MSL, where they developed the approved procedure MSL currently follows for hot patching. However, due to its more conservative risk posture, a formal M2020 hot patch procedure has yet to be developed.

Significant post FSW Transition Regression Testing is an Option Once a full FSW release is available for regression and Engineering Change Request (ECR) testing, each subsystem completes its testing prior to holding a Software Review Certification Record (SRCR), at which approvers are polled for their acceptance of the FSW release prior to uplink. At the end of an SRCR, it is common for there to be a small set of liens that may include a follow-up test. In S8.1, there were 14 RO ECRs, 9 of which described 14 changes to the Mobility FSW. During the S8.1 test period, there was a significant issue that delayed Mobility testing on the Vehicle System Testbed (VSTB) engineering model of Perseverance. On November 6, 2024, the testbeds were updated with S8.1 and the regression test campaign kicked off. But by then, several wheel/steer actuator (WSA) motors had been harvested from the VSTB to support additional life testing, leaving the VSTB in a state where driving was precluded. On March 11, 2025, the VSTB was released in a configuration where the middle wheels were missing their WSA, which enabled Mobility regression testing to begin with the middle wheels free rolling. The SRCR was only delayed from May 5, 2025, to June 17, 2025 in an effort to not impact the FSW transition schedule. But that delay was not enough time for the Mobility team to complete its testing. So the project approved a strategy for RO to complete regression testing only for S8.1 Mobility changes that could not be disabled, but to disable in flight (via parameters) new features until their regression testing is complete. Perseverance FSW transition to S8.1 occurred the first week of August 2025. The project decision to allow new Mobility features to remain disabled until regression testing had completed and to proceed with FSW transition as scheduled was an unusual but reasonable accommodation. Given ongoing staffing challenges, S8.1 Mobility regression testing of new features is still in progress.

New High-Value SNC Capabilities can be Developed in Extended Mission The development of high value capabilities during an extended mission are commons for mobility. In April 2024, 3 years after landing, the *AutoNav Roundtable* group was formed to improve Perseverance's ability to drive further in challenging terrain. This collaboration led to 9 Mobility ECRs in S8.1 FSW. Less common is the development of high value SNC capabilities during an extended mission. One such capability had its genesis in a discussion with the Science team about how unfortunate it would be if an extremely valuable target were encountered after all sample tubes were filled and sealed. So during the spring of 2025, with 8 sample tubes remaining, the Science team requested the SNC team develop a capability to dump an acquired core sample out of a tube, in case a higher value target is encountered. On May 2, 2025, the SNC team released a sample dump capability at terrain tilts up to 20°. The Science team can direct SNC to leave an acquired core sample unsealed, in case

they identify a better rock in the future. The sample dump process has two options, one with and one without percussion. With percussion will have a much higher likelihood of success and leave the tube in a somewhat cleaner state, while no percussion would help preserve actuator life.

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