First 210 solar days of Mars 2020 Perseverance Robotic Operations – Mobility, Robotic Arm, Sampling, and Helicopter

Vandi Verma, Frank Hartman, Arturo Rankin, Mark Maimone, Tyler Del Sesto, Olivier Toupet, Evan Graser, Steven Myint, Kevin Davis, Douglas Klein, Justin Koch, Sawyer Brooks, Philip Bailey, Heather Justice, Marco Dolci, Hiro Ono
Jet Propulsion Laboratory
4800 Oak Grove Dr.
Pasadena, CA 91109
verma @jpl.nasa.gov

Abstract— **This paper includes a summary, lessons learned, and upcoming plans from the first 210 Mars solar days (sols) of NASA's Mars 2020 Perseverance rover mission. The focus of the paper is on Robotic Operations, which is the team with the primary responsibility for strategic planning, uplink commanding and downlink analysis for rover mobility and navigation, robotic arm operation, the sampling and caching capability including coring, the adaptive caching assembly and the 2nd sample handling robotic arm, and the interface to the Mars helicopter Ingenuity. As of Sol 210 the rover has driven 2663.65 meters, executed 20764 robotic arm and sampling commands, and has successfully completed 13 helicopter flights covering 2382 meters horizontal distance. It includes Operations Readiness Tests executed in preparation for landing, landing and initial checkouts, strategic route planning to the science destination and waypoints, and surface checkout of all of the robotics capabilities of the rover. It also discusses the strategic planning and tactical agility needed to interleave science investigations and the technology demonstration of the Mars helicopter flights where a minimum distance had to be maintained between the rover and helicopter during flights. It discusses the challenges with planning robotic operations and addressing anomalies with the larger uncertainty present during early mission operations. It also discusses the impact on robotic operations from lessons incorporated from previous missions.**

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1. INTRODUCTION

The Mars 2020 Perseverance rover is designed for science exploration. Its prime mission will last one Martian year, or about 687 Earth days. The objectives of the mission are to collect and cache up to 37 rock and regolith samples for potential future return to Earth, perform in-situ observations to study Geology and Astrobiology, and prepare for human exploration [1]. Figure 1 shows a "selfie" [2] image that Robotic Operations (RO) and the Perseverance mission operations team developed and executed, capturing a stunning view of the rover and helicopter side by side on Mars.

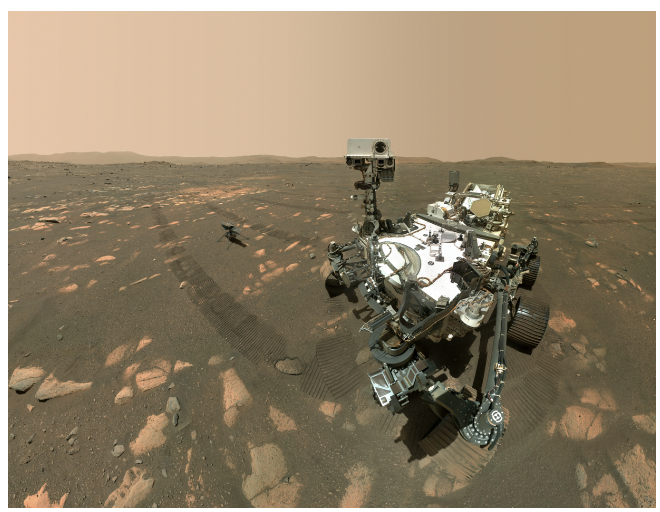

Figure 1: Perseverance and Ingenuity selfie taken by the rover on Sol 46 after deploying Ingenuity at Wright Brothers airfield and before the first flight.

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As of sol 210 the rover has driven 2663.65m and the helicopter has completed 13 flights covering 238m horizontal distance. Figure 2 shows the Perseverance and Ingenuity paths explored as of Sol 210.

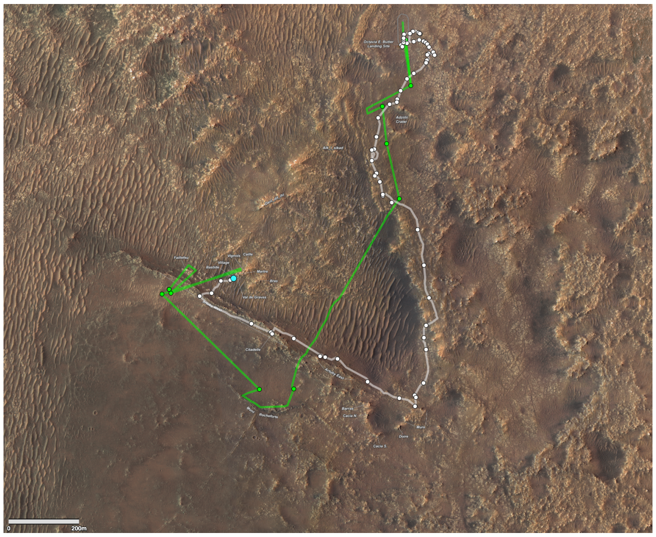

Figure 2: Figure showing an Orbital map view of the Perseverance and Ingenuity paths as of Sol 210. Perseverance locations are shown in white and Ingenuity in green.

2. ROBOTIC OPERATIONS ROLE

Past Mars rover missions have organized their personnel into two teams, one for uplink and one for downlink. Mars 2020 retains that breakdown, but adds a third: the Robotic Operations role. One of the lessons learned from those earlier missions is that the robotics-specific roles (driving, arm, sample handling) are so tightly coupled, those sub-teams need to work more closely together.

The RO team on the Mars 2020 mission is responsible for strategic planning, uplink commanding and downlink analysis for the robotics aspects of the mission. The areas it is responsible for include mobility, robotic arm, turret, sampling and caching, and the interface to the Mars helicopter Ingenuity.

Due to the time delay in communicating between Earth and Mars, there is typically at most one opportunity to uplink commands each Mars solar day (sol). Commands sometimes span multiple sols in a single planning cycle. This limited ability to intervene results in significant robotic uncertainty that must be accounted for in operations. It also makes the RO area well-positioned to take advantage of autonomous onboard capabilities. The mission is science driven with goals to collect and cache samples for potential future return to Earth, study Geology and Astrobiology in situ, and prepare for future human exploration. NASA Mars missions are discovery-driven with plans for each sol being based on data analysis and science discussion of the previous sol(s) telemetry. Onboard autonomy must therefore be operated to satisfy science and engineering goals and RO must account for the ways in which the rover and helicopter may execute their plan sand possible interactions with the environment. RO tools, processes and sequences are categorized into the following four distinct areas:

Rover Mobility and Navigation for driving the rover between science targets. Selection of these targets is based on RO guidance on navigability and duration, i.e., the number of sols needed to reach them.

Robotic Arm Operation for planning robotic arm motion for all activities. This ranges from deploying and positioning the robotic arm and turret-mounted instruments and tools (Figure 3) for analyzing surface targets to docking and positioning the robotic arm relative onto or near the rover body itself, for various science and engineering activities.

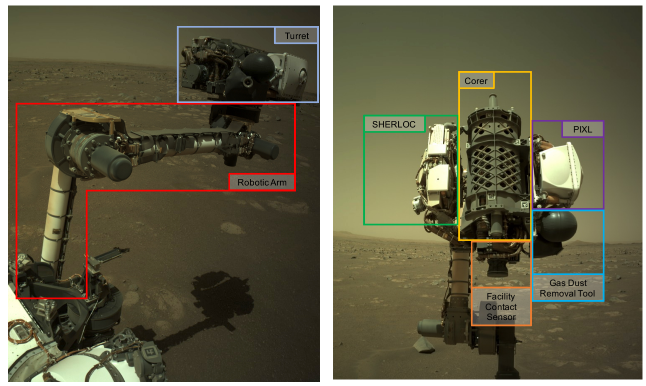

Figure 3: Components of the robotic arm and turret labeled in Navigation camera images.

Sampling and Caching Operation for operating the Drill Corer, the Adaptive Caching Assembly (ACA), and the Gas Dust Removal Tool (gDRT).

Mars Helicopter Ingenuity Operation for the rover interface to the helicopter including uplinking commands to Ingenuity and ensuring the rover acts as a communication relay for the helicopter.

The Mars 2020 project divides mission operations into three categories of operational roles. All three categories are staffed each planning day by all the project teams:
Campaign Implementation where plans for the next few sols are developed
Tactical Uplink where commands are created, validated, and uplinked for the current sol, and
Downlink where the sol that just completed is evaluated [3].

The RO team is organized into four sub-teams:

1. **Rover Planning (RP)** team that commands mobility and robotic arm operations.
2. **Downlink Analysis (DL)** team that evaluates past mobility and robotic arm operations
3. **Sampling and Caching (SNC)** team that commands sampling operations.
4. **Helicopter Integration Engineer (HIE**) team that commands Ingenuity.

		SNC OPERATIONS ROLE			
		SNC-CI	**SNC-1**	**SNC-DL**	**SNC-2**
EARTH CALENDAR DAY	**Day 1**	Operator C	Operator B	Operator A	Operator A
	Day 2	Operator D	Operator C	Operator B	Operator B
	Day 3	Operator E	Operator D	Operator C	Operator C

Table 1: Example of a rotation staffing schedule for SNC operations.

All these teams support the three operational roles, and have adopted a form of shift rotation pattern. An SNC operator will typically staff three consecutive days of tactical operations, rotating from Campaign Implementation (as SNC-CI), to Tactical Uplink (as SNC-1), to Downlink (as SNC-DL). When the Downlink shift is complete (typically within two to three hours), SNC-DL will joins the ongoing Tactical Uplink shift on the same day as SNC-2. This rotating schedule allows each operator to "follow" an activity through the operations process, instead of handing the activity off between multiple people. Additionally, if an activity fails, the operator who planned it and assessed it during downlink will be available as SNC-2 to help SNC-1 recover from the anomaly and re-plan the activity. A typical staffing schedule is presented in Table 1, showing each operator rotating from SNC-CI, to SNC-1, to SNC-DL and SNC-2. HIEs on Mars time followed a similar rotation pattern, but with a single uplink HIE instead of SNC-1 and SNC-2. RPs often follow a similar CI -> Tactical transition, except that RP downlink is performed by a separate DL team.

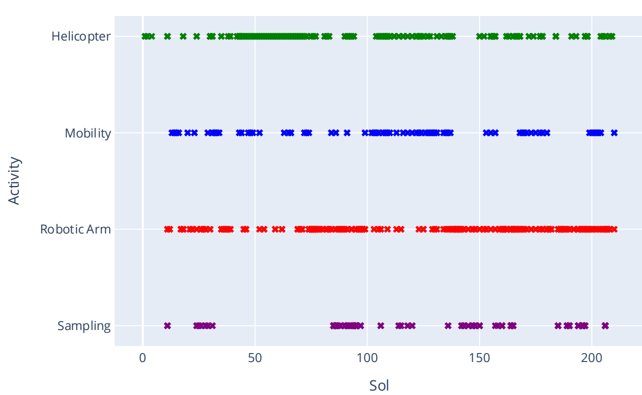

Figure 4: A plot showing interleaved robotic operations activities by sol for the first 210 sols.

Lessons learned from prior missions have resulted in the creation of the RO team, with RO engagement from early mission concept, through design, development and testing. Figure 4 illustrates the extent of RO activities in mission operations, with all teams having significant activities throughout the mission lifetime.

By design RO is engaged in:

- Robotics Systems Engineering
- Robotics Flight Software
- Robotics Mechanical Engineering
- Robotics Verification & Validation
- Human Robot Interaction Tools and Visualization
- Ground Software
- Operability
- Technology Development

3. Rover Mobility

Mobility and navigation operation controls the mechanical hardware related to the mobility of the vehicle including the wheels, suspension, drive and steer actuators, Inertial Measurement Unit (IMU), and the flight software that controls the rover mobility and navigation. Mobility and navigation flight software also make use of the rover Engineering cameras for terrain assessment and Visual Odometry computations. In addition, Perseverance also has avionics and dedicated processors for motor control - The Rover Motor Control Assembly (RMCA) with a Sparc processor, and stereo processing - the Vision Compute Element (VCE). Interactions between all aspects of mobility and mobility-adjacent systems must be considered during operations.

Figure 5: Comparison of Curiosity (left) and Perseverance (right) wheels.

Like the Mars Exploration Rovers (MER) and the Curiosity rover, Perseverance has a six-wheeled rocker bogie passive suspension design with corner-wheel steering and six-wheel drive. The wheels are constructed of aluminum with curved titanium spokes and each have an outer diameter of 52.5cm and width of 33.56cm. The design directly influences the drive path rover drivers generate during operations. The mobility system functioned as the landing gear during touchdown at the end of the mission's Entry, Descent, and Landing, which also influenced its design. Due to the wheel wear challenges Curiosity encountered in Gale crater the Perseverance wheels were designed to improve traction and durability (Figure 5). The Perseverance wheels have a thicker skin, larger diameter, a gentle wave grouser pattern, a different post-fabrication treatment and a narrower width to reduce mass.

Vision Compute Element (VCE) Perseverance has two RAD750 computers used for surface operations, the Rover Compute Element (RCE) for general purpose computing and the VCE for dedicated Computer Vision tasks like Visual Odometry and Stereo Vision computations for terrain understanding. The VCE is connected to a Xilinx Virtex-5

FPGA which performs stereo correlation and much of the VO processing so quickly that the rover is typically able to drive continuously while simultaneously maintaining position knowledge and updating its terrain heightmap; this capability is called *Thinking-While-Driving (TWD).*

Drive Primitives Basic mobility commands that give RPs direct control of the rover include arc and turn-in-place. Arcs are commanded with path length and desired change in heading, choice of drive mode (Guarded or not), and optionally may be told to terminate early if a goal point changes from being in front of the rover to being behind it. Like Curiosity, Perseverance is electrically unable to actuate all 4 steer motors while also actuating the 6 drive motors. Thus all driving operations may not perform driving and steering simultaneously. This implies that if steering is required, the rover must stop driving, steer the wheels, then continue driving. For arcs commands, the behavior is open loop, terminating when precomputed limits have been reached: steering motors are first commanded to achieve the desired curvature, then wheels are driven until at least half have reached the precomputed rotation amount needed to achieve the commanded distance on idealized flat terrain.

Blending arcs Perseverance has the ability to drive continuously, blending adjacent arcs together if they have the same curvature and direction and thus same steering and drive actuation profiles. When blending, motors are not stopped between individual arc steps. Commanded arcs will be blended together if possible. and if the series of arc requests is received with enough time to blend them, with a few exceptions. E.g., turn-in-place maneuvers are never blended.

Waypoint Driving: For covering longer distances, a majority of the driving is done in using a high-level MOB_GO_TO command to drive to a specified waypoint. The rover navigation flight software automatically computes arcs and turns iteratively that execute the next calculated step toward the waypoint, based on the current position estimate.

Visual Odometry improves the accuracy of the rover position estimate during motion [5]. It autonomously detects 3D features in nearby terrain using stereo imaging and tracks their motion across short steps (generally 1 meter). It uses that knowledge to generate a 6 degree-of-freedom delta pose measurement (in both position and attitude), and is currently configured to apply only the 3 DOF position update to the onboard position estimate. VO is the only system onboard capable of measuring translational slip, and fault monitors like Max Allowed Slip Fraction are only evaluated when new VO results become available.

Terrain Mapping constructs and maintains a 2.5D Digital Elevation Map (or Heightmap) of terrain within 30 meters of the rover's current position. The ACE algorithm [6] uses the Heightmap to determine whether particular drive paths are safely traversable when driving in either Guarded or AVOID_ALL path modes.

4. ROBOTIC ARM

The Robotic Arm (RA) (Figure 3) extends two meters from the front of the rover chassis. It includes five actuators separated by two large titanium links. Each actuator is driven by a brushless DC motor and held in place by friction brakes. A hall effect sensor tracks motor input shaft position while a dual speed resolver monitors actuator output position. There is a full redundant force torque sensor (FTS) at the end of the robotic arm, used for closed loop load application and inadvertent contact monitoring.

The Turret is attached to the end of the RA. The primary structure of the Turret is a rotary percussive coring drill. The Corer can be used to abrade the surface to create a shallow, smooth, circular patch for instrument observations. The Corer can also extract rock and regolith samples. The Facility Contact Sensor (FCS) is mounted to the back of the Corer and is used to detect the surface for improved RA placement accuracy. The Gas Dust Removal Tool (gDRT) uses short bursts of compressed nitrogen to clear dust from surfaces to better expose rocks for scientific investigation. After a sample has been acquired, the RA docks the Corer against the Bit Carousel mounted at the front of the rover chassis, for further processing by the Adaptive Caching Assembly (ACA).

In addition to abrasion and sample collection tools, the Turret also includes two scientific instruments. The Planetary Instrument for X-ray Lithochemistry (PIXL) is an X-ray fluorescence spectrometer mounted on an articulated hexapod structure [7]. PIXL's Optical Fiducial System (OFS) projects a grid of lasers onto the surface which is imaged by the Micro Context Camera (MCC) to precisely determine the surface location. PIXL's hexapod can target specific features of interest, compensate for RA placement uncertainty, and compensate for thermal drift during long-duration observations. PIXL observations acquire high spatial and spectral resolution data revealing the chemical composition of the surface it is analyzing. The Scanning Habitable Environments with Raman and Luminescence for Organics and Chemicals (SHERLOC) instrument contains two instrument boresights [8]. The spectroscopy boresight generates spatially resolved chemical maps using fluorescence and Raman spectroscopy with an ultraviolet laser and a context imager. The Wide Angle Topographic Sensor for Operations and eNgineering (WATSON) [8] boresight contains a high resolution camera. WATSON is used for high standoff context imaging and lower standoff imaging that can resolve detailed surface texture. WATSON is also used for rover self-inspection to serve a variety of purposes.

5. SAMPLING AND CACHING

Sampling and caching elements [4] are present both inside and outside of the rover body to enable surface interactions, sample transfer, and caching. The Coring Drill (Corer) constitutes the main body of the turret. The Gas Dust

Removal Tool (gDRT) and the Facility Contact Sensor (FCS) are mounted on the turret. These work together with the RA to provide the sample acquisition, abraded surface preparation, and proximity science functions. The ACA is a network of assemblies largely inside the front belly of the Rover, which combine to perform the sample handling and caching functions of the mission (Figure 6). The ACA primarily consists of the Bit Carousel, the Sample Handling Assembly (SHA), End Effector (EE), Sample Tubes and their Sample Tube Storage Assembly (STSA), Seals and their Dispenser, Volume, and Tube (DVT) Assembly, the Sealing Station, the Vision Station, the Cover Parking Lot, and additional supporting hardware. These components attach to the Caching Component Mounting Deck (CCMD) that is integrated with the Rover interior.

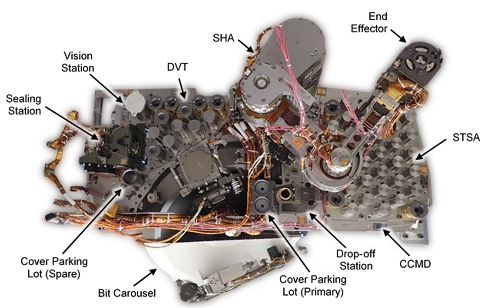

Figure 6: Image of Adaptive Caching Assembly showing the stations with Sample Handling Arm deployed [4].

6. Helicopter

The Mars Helicopter, Ingenuity, is a technology demonstration to test powered, controlled flight on another world for the first time [10]. It landed on Mars attached to the belly of the Perseverance rover. A debris shield protected the helicopter during entry, descent, and landing. There were requirements on how far the debris shield had to be deployed from the airfield and on the terrain characteristics of the airfield [11]. The RO and helicopter teams were responsible for selecting suitable sites for the debris shield deployment, an airfield for deploying Ingenuity, and a rover observation location for first flight. The RO team was responsible for driving to these locations including the critical drive off the helicopter after it was deployed (Figure 7), and for imaging all of the intermediate steps of the deployment with the WATSON camera at the end of the robotic arm.

Figure 7.: Ingenuity helicopter and Perseverance rover tracks as seen from the rovers Rear Hazcam after the successful deployment and drive off on Sol 43

The RO HIE team performs the operations planning for uplink and downlink for every sol of Ingenuity helicopter operations.

7. Robotic Operations Ground Tools

There is a large suite of tools used by RO for uplink planning. The main rover planning tool is the Rover Sequencing and Visualization Program (RSVP) [12]. Figure 8 shows RP mobility workflow at a high level and the tools that are used to evaluate images, sketch a drive using macros, simulate on meshes derived from stereo navigation camera and orbital images, visualization of the drive inside high resolution images, to checking and validation of the commands generated via macros.

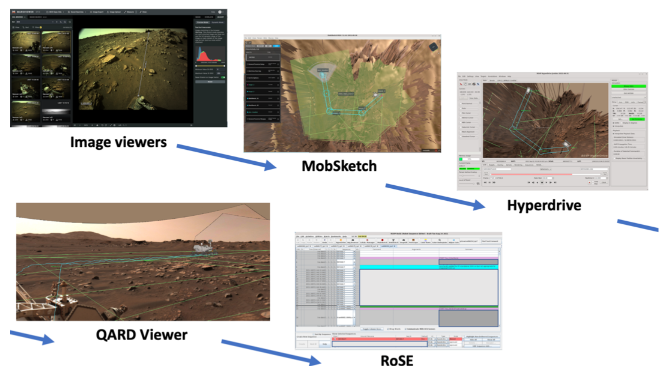

Figure 8: Robotic Operations mobility tools and simplified high level workflow.

Macros In addition to visualization and commanding tools, RPs extensively use abstraction via JavaScript macros for efficient commanding that is strategically reconfigurable. Each sol, operators send commands to the rover packaged into sequence files. These sequences can vary from hundreds to even thousands of lines of commands for complex activities. Figure 9 shows the number of commands by sol sent to the rover by robotic operations for the first 210 sols of the mission. The first 67 sols of this was during Mars time operations. To speed up sequence writing, operators use macros to generate blocks of sequence commands through the input of simplified arguments. Macro usage leads to faster development of sequences using standardized commanding paradigms. Macros are also used by higher level tools--such as MobSketch and ArmSketch--to generate sequences using a graphical, no-code, interface.

Macros expansion occurs in the Robot Sequence Engine (RoSE) software tool which is part of the Robot Sequencing and Visualization Program (RSVP). Macros are categorized by sequence type such as arm, trav (mobility), snc (sampling), and heli. Within each category, macros are listed with a short description of their usage. Macros are the primary means of commanding operations generated by the ArmSketch and MobSketch tools into RoSE, but they may also be expanded manually. After selecting a macro, a prompt will ask the user to input arguments through a dropdown selection or manual entry.

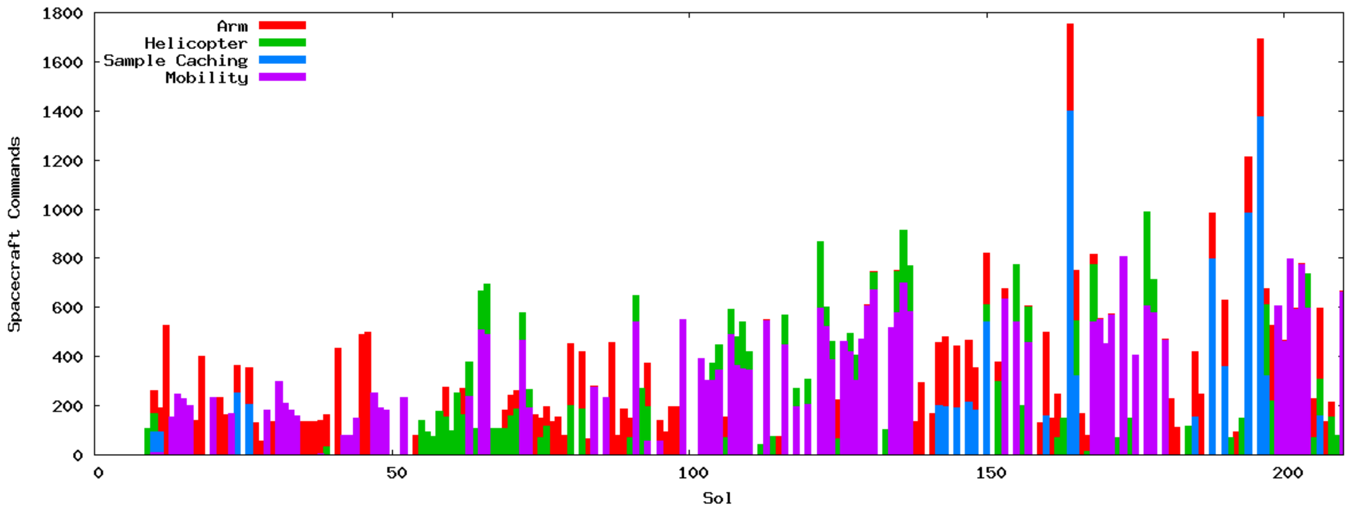

Figure 9: Plot showing the number of spacecraft commands by sol sent to the rover by Robotic Operations for the first 210 sols of the mission. Note that spacecraft commands are shown here and low-level sampling script commands are not included in this count.

These inputs can be a text field, floating point number input, or a selection from a list of options. Once inputs are submitted, a block of commands will then be inserted into RoSE at the location that was selected prior to expanding the macro. Some macros connect to external tools to generate more complicated outputs.

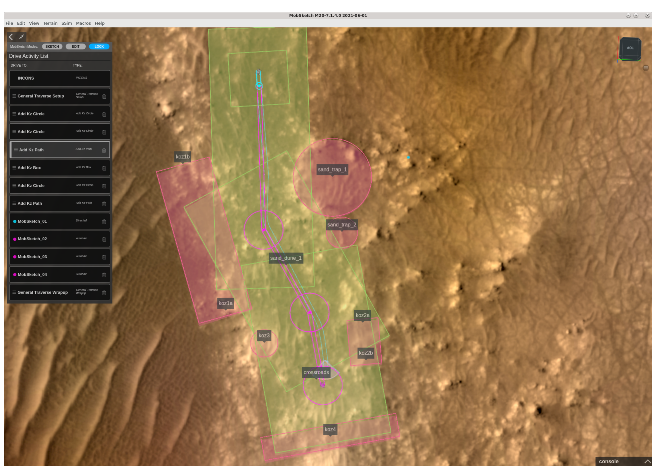

Figure 10: MobSketch image showing the RP sketch of Sol 134 drive with directed and autonomous navigation segments. Also shown are the geometric Keep In Zones in green and Keep Out Zones in red which RPs create to keep AutoNav safe from non-geometric hazards that cannot be detected onboard.

Macro implementations are updated strategically as new mission capabilities are identified and approved. When changes are proposed to a macro, a suite of unit tests is run against the entire macro library to display resulting changes in output. This helps catch when logic changes in one section of one macro may impact others as well. Macro developers also ensure that macro-generated code adheres to the mission Flight Rules, a collection of system restrictions and usage guidance intended to prevent faults and invalid or unsafe behaviors on the rover

These macros and higher level graphical tools are important steps toward reducing the amount of time needed to plan operations each day. They allow more time to be spent on refining science targets, assessing safety of instrument placements and drives, and ensuring the highest science return per sol. The routine time spent writing commands and arguments is drastically reduced. This leads to fewer opportunities for operator errors as macros are strategically reviewed and approved to deteremine their documented use case.

To expedite mobility planning, the rover planner team utilizes a graphical interface called MobSketch and a macro-driven backend that automates sequence expansions.

MobSketch provides a 3D view of the rover and surrounding terrain, where users select and configure activities corresponding to pre-defined rover capabilities. Activities range from complicated autonomous drive legs (shown in) to simple parameter configuration and include various options that are used to customize the behavior. For example, a single activity represents a basic "directed" (non-autonomous) drive leg (Figure 11), with options that include path mode (Unguarded or Guarded) and imaging mode (none, VO, or VO and Mapping). Figure 12 shows the path path from Figure 11 followed by an AutoNav segment. Each activity maps directly to a macro that translates the options and activity inputs into a block of flight software commands.

ArmSketch RP robotic arm and sampling workflows follow a similar pattern of abstraction. Figure 13 shows an example workflow at a high level where multiple tools are used to evaluate images and refine targets, sketch the robotic arm placement, simulate on meshes derived from stereo hazard cameras, visualize the robotic arm motion, and check and validate the commands generated via macro invocations generated by ArmSketch. ArmSketch provides a 3D visualization interface for sketching arm and sampling activities similar to MobSketch for mobility.

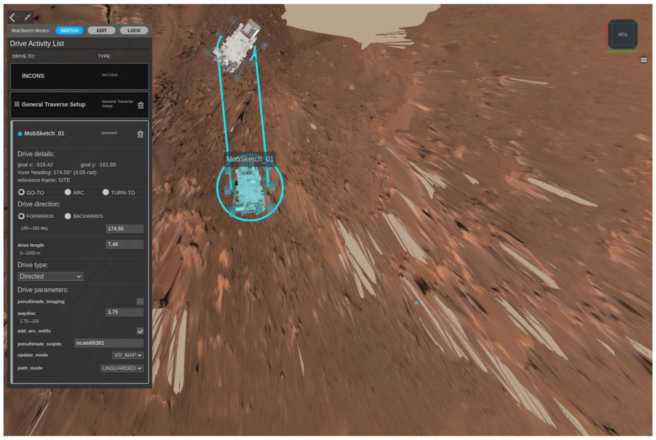

Figure 11: Example of a directed drive leg in MobSketch showing options strategically exposed to RPs.

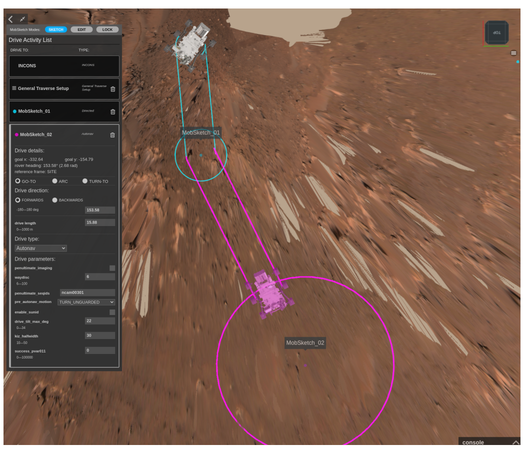

Figure 12: Example of a directed drive followed by an AutoNav drive. Here only the second leg is displaying the available options in the box on the left.

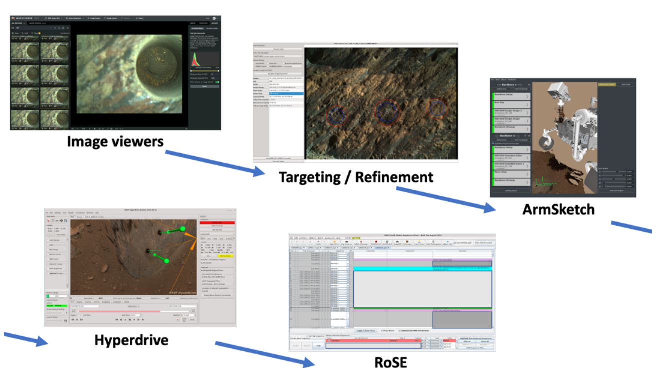

Figure 13: Robotic Operations robotic arm / sampling tools and simplified high level workflow.

8. First 210 sols of Robotic Operations

Strategic Route Planning

The Perseverance landing ellipse was 7.7km x 6.6km. Although it was much smaller than the prior missions due to new capability on Mars 2020 such as the Lander Vision System (LVS) and range trigger, it is still quite large. Various landing scenarios were analyzed a few months before landing resulting in the development of 3 main strategic routes that all aim to reach the West side of the Jezero crater rim within the prime mission timeline but assume different starting locations. These are illustrated in Figure 14: 1) landing on the Delta, 2) landing just off the Delta, considered to be the most likely outcome given the landing uncertainty ellipse, and 3) landing far East of the Delta, near the Remnants.

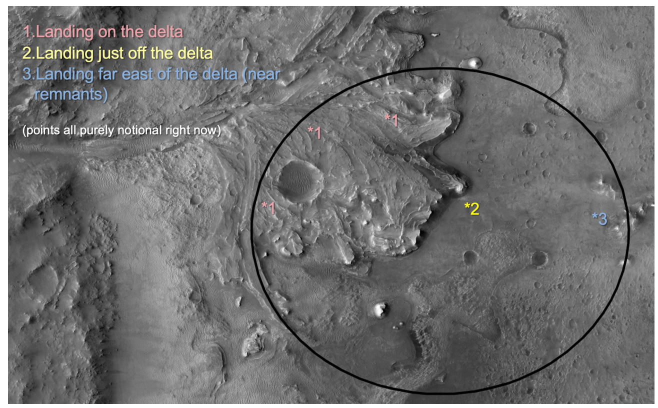

Figure 14: Three landing scenarios analyzed prior to landing for strategic route planning.

This was valuable and enabled the science team and Rover Planners to start thinking about the prioritization of the various science targets of interest as well as their accessibility and the best routes the rover could take to reach them.

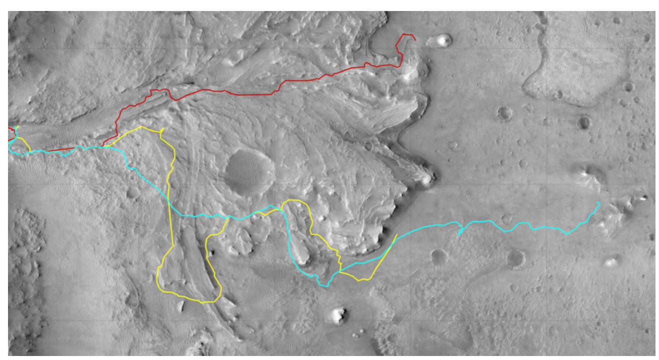

Figure 15: Strategic routes developed for each of the three landing site scenarios (yellow: near Delta, red: on Delta, cyan: far East.

shows the strategic routes developed for each of the 3 landing site scenarios up to reaching the western edge of the Jezero crater rim. Note that for the scenario that assumes landing on the Delta, the route has the rover first drive East and climb down from the Delta to go sample the smooth crater floor unit before turning around and driving back West up the Delta the same way it came from.

On February 18 2021, the Perseverance rover landed in a location further from the Delta than expected but not quite as far as the "far East" scenario. This is because the LVS system diverted the rover South to avoid landing in a seemingly hazardous terrain that has since been named Séítah. In order to reach the Delta, the rover now had two options: either drive counterclockwise or clockwise around Séítah, as illustrated in Figure 16.

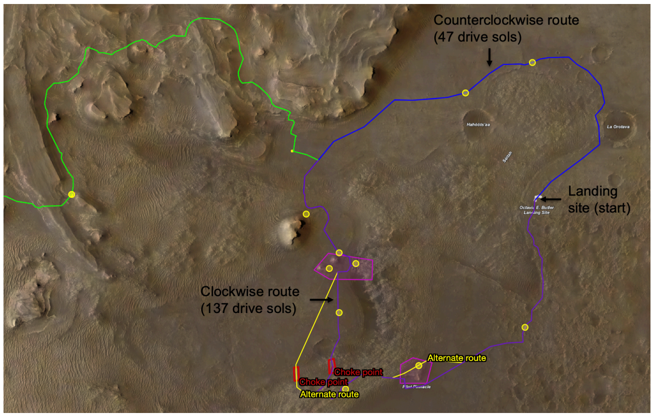

Figure 16: Clockwise (CW) and counterclockwise (CCW) routes to reach the Delta from the landing site.

The clockwise route, although more interesting from a science perspective, was estimated to be almost 3 times longer to drive, due to the rover having to traverse a field of sand dunes which would have taken many human-directed short drives, as opposed to the counterclockwise route where autonomous navigation (AutoNav) can be relied upon to drive much further each sol.

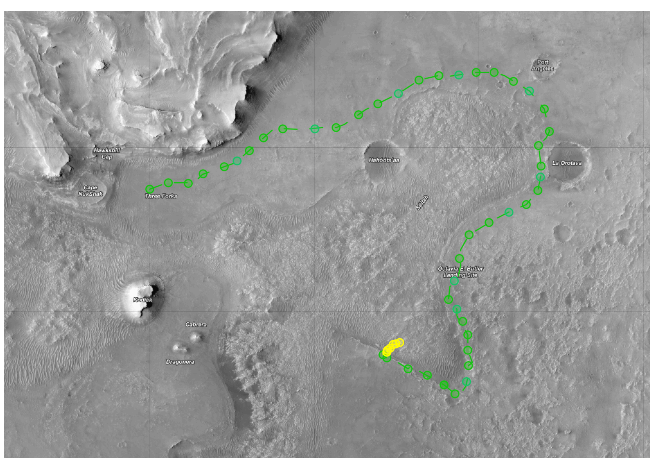

Figure 17: The chosen strategic route drives clockwise from the landing site to sample high-value science targets in southern Séítah, and then goes back up to the Delta via the counterclockwise "highway" to take advantage of fast traverse enabled by AutoNav.

As a compromise, the M2020 team chose to drive part of the CW route, to sample exposed bedrock near the Southern tip of Séítah and toe-dip into Southern Séítah as part of the Green Zone campaign. The plan to drive to the Delta as quickly as possible is to travel back to the landing site and beyond with AutoNav along a CCW route, as illustrated in Figure 17.

The SOX Commissioning Phase

The Surface Operations Changeover (SOX) phase of the mission began shortly after landing and ran until sol 98 [13]. SOX was split into four sub phases:

- 1A: Basic software state and rover state updates and checkouts
- 1B: Basic actuator checkouts including mobility and minor arm motion
- 2A: Higher level functional checkouts and instrument checkouts
- 2B: Higher level functional checkouts and instrument checkouts (Continued)

The purpose of the SOX mission phase was to check all the necessary functionality required to execute the prime science mission. Each subphase of SOX systematically tested increasingly higher order functionality starting with low level aliveness checks in 1A and finishing with full system tests including multiple subsystems in 2B. Originally SOX 2 was one subphase by itself, but due to the need to execute the helicopter test as early as possible, SOX 2 was split up into two subphases with a month for helicopter ops in the middle. From an RO perspective, there were no major liens coming out of SOX after the checkouts, and the mission smoothly continued to nominal operations [14].

Helicopter Site Selection and Rover Observation Location

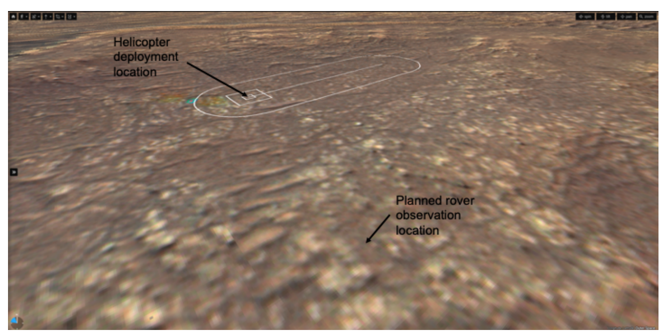

Figure 18: Selected Flight Zone and Rover location at Van Zyl overlook for observing helicopter demonstration flights.

In parallel with SOX, RO HIEs worked with the Helicopter project and Strategic Route Planning team to find a safe Deployment Area for the helicopter with an Airfield and Flight zone that met the requirements. These are discussed in detail in [8]. The helicopter does not have the capability to perform hazard avoidance during landing and relies on the ground-based fight path to select an appropriate landing area that will maximize the likelihood of a successful landing for each flight. The initial search strategy was to evaluate the terrain in the vicinity of the rover to find the closest Flight Zone to deploy the helicopter. If detailed analysis resulted in discovering that it was not suitable, the next alternative that was identified was to travel Northeast about 300m from the rover. Analysis of these images determined that the site met the requirements with minor deviations. In addition, an observation location for the rover had to be identified that met the constraints of being >45m from the helicopter while providing line of sight for communication and imaging and being reachable by the rover at a fast pace with the mobility capability commissioned at that point in the mission. shows the rover observation location that was ultimately chosen, 47m from the edge of the helicopter flight zone.

Mobility Modes and Performance

Perseverance supports multiple driving modes, giving Rover Planners flexibility in how the rover is commanded. The main modes used so far include:

Directed Nonimaging: Basic driving with no autonomous image processing.

Directed_VO: Basic driving with Visual Odometry always active, keeping the position estimate as accurate as possible and always checking for unexpectedly high slip.

Mapping: Basic Directed driving with both Visual Odometry and Map Building, but no onboard assessment of the terrain; this mode just builds a map, it does not use it to evaluate the terrain geometry.

Guarded: Like Mapping mode, but also consults the onboard map to determine whether the planned step is safe using the ACE algorithm. If any planned motion is deemed unsafe, driving will be halted with an UNSAFE or KEEPOUT fault depending on the obstacle type.

AutoNav (AVOID_ALL): The primary autonomous driving mode, this also relies on both Visual Odometry and Mapping to understand the geometry of the world. And in this mode the rover is given the freedom to select the safest and most effective path on its own. In this mode it is fully self-driving, except that human Rover Planners will select the goal it drives toward.

Although Perseverance's wheel speed is nearly identical to Curiosity's (just over 4.2 cm/s), Table 2 shows the drive rates achieved by Perseverance using each of these modes during these first 210 sols. These rates show a dramatic improvement over those achieved in earlier missions [15]. They demonstrate the success of the Thinking While Driving architecture, using an extra RAD750 CPU and FPGA to speed up processing of high resolution images for autonomous terrain understanding. How successful has it been? During just these first few months, Perseverance has already broken several mobility records set by earlier rover missions.

Most use of Autonomous Surface Navigation

Perseverance is the first planetary rover to have driven more than 50% of its distance autonomously, using its AVOID_ALL, GUARDED and Mapping drive modes, as shown in Table 2 and Figure 19. In comparison, the Sojourner rover demonstrated only a limited hazard detection capability with 20 terrain samples per observation, while MER and MSL missions had a capable (albeit more conservative) hazard detection and avoidance capability that kept the three rovers safe but was only used for less than 10% of each mission's overall odometry [15].

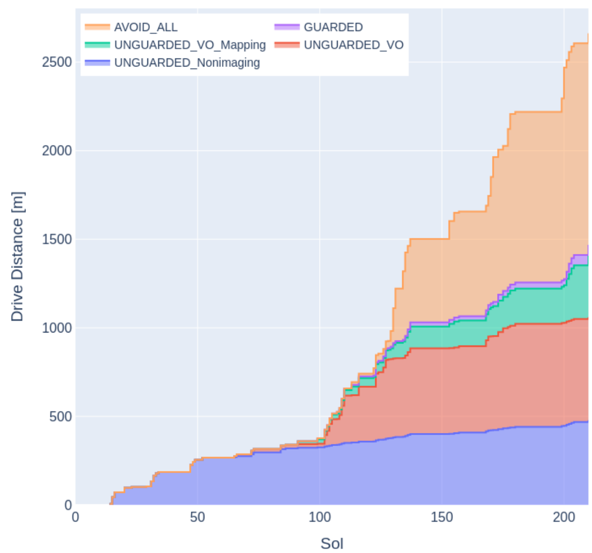

Figure 19: Cumulative Odometry by drive mode for first 210 sols

Longest Single-Sol Autonomous Drive

On Sol 200 Perseverance drove 167 meters autonomously, a new interplanetary record. The prior record was 119 meters from sol 130, which was only the second nominal AutoNav drive commanded post-checkout. Before that, Opportunity had held the record with 109 meters from its sol 384 in February 2005 [15].

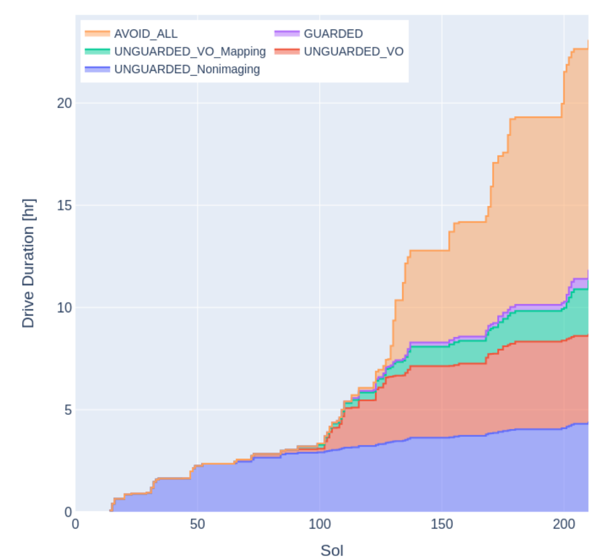

Figure 20: Cumulative duration by drive mode.

Fast Visual Odometry

Perseverance is the first planetary rover able to perform Visual Odometry processing in the background while driving continuously. While Curiosity made extensive use of Visual Odometry, employing it for 91% of its driving after the Mars-year duration Prime Mission ended, it only achieved an average drive rate of 46 m/hr. Perseverance has been able to use VO at an average rate of 135 m/hr (Table 2), a 3x improvement. Figure 19 and Figure 20 show that duration for VO and AutoNav (AVOID_ALL) drives is similar to Unguarded drives with no imaging, as is the effective drive rate (Table 2).

During the first 50 sols, all of our driving was Directed, i.e. executed without using onboard vision processing to better understand the terrain. This was by design, as the first two months were spent validating all the spacecraft instruments and operations; vision autonomy checkout was not scheduled until later. That limited our single-sol achievable distance to driving no more than 30 meters radially from our starting point, since that was the maximum distance we could drive with reasonable confidence of the hazard localization (in the terrain meshes the ground tools could generate at the time)

	distance [m]	duration [hr]	effective rate [m / hr]
GUARDED	58.13	0.50	116.62
AVOID_ALL	1195.00	11.25	106.27
UNGUARDED_Blind	477.56	4.41	108.32
UNGUARDED_VO	582.00	4.29	135.69
UNGUARDED_Mapping	0.00	0.00	0.00
UNGUARDED_VO_Mapping	350.00	2.65	132.04

Table 2: Drive Rate Summary for first 210 sols (sols 14-210 covering 68 drives).

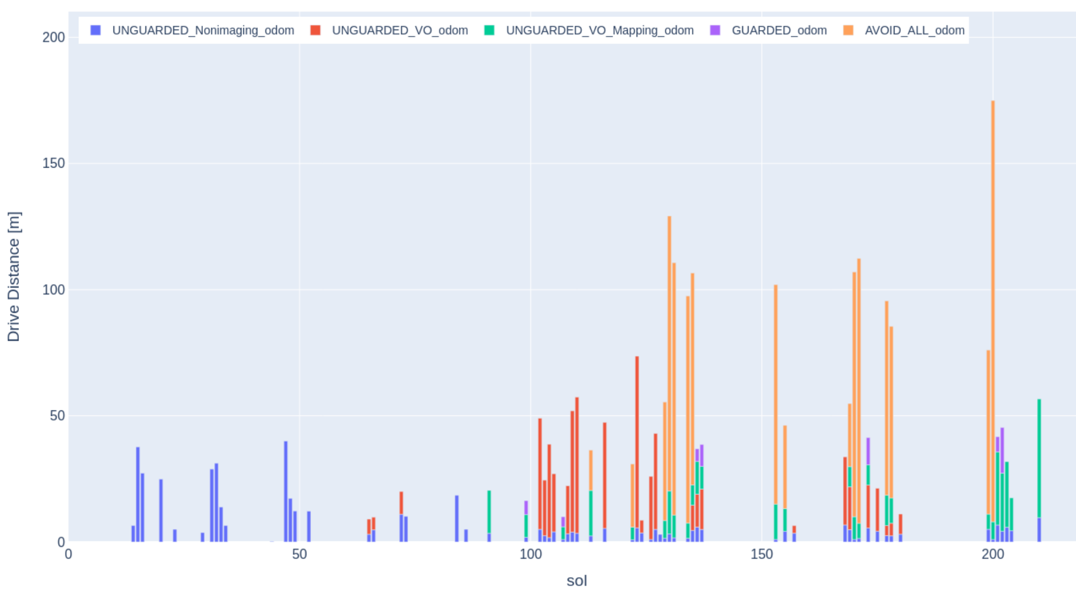

Figure 21: Drive distance by drive mode for first 210 sols.

without any Visual Odometry onboard. The next month was dedicated to the planned Helicopter technology demonstration with the rover providing communication relay and documenting the flights with videos and imaging.

First 50 sols of directed driving

shows a breakdown of each sol's commanded odometry by drive mode. It provides a view of the planned evolution of mobility strategy as functionality was commissioned in stages. It also highlights those sols where Helicopter or Sampling operations took precedence, since Mobility was avoided on those sols. The same information is available in a cumulative plot in Figure 19.

Helicopter technology demonstration

Prior to deploying the helicopter, the rover first needed to drop the helicopter debris shield that protected the helicopter from impacts during the rover's entry, descent, and landing

(EDL). This shield was ejected from below the rover a short distance away from the flight zone on sol 30. The rover next returned to the flight zone and began the deployment process. The Mars Helicopter Delivery System (MHDS) was the mechanism that placed the rover from the underbelly of the rover to the surface of Mars, completing the helicopter's last meter of its EDL process. This delivery was outlined across 7 unique steps requiring at least that many sols. Throughout the various steps, RP's commanded the robotic arm to take WATSON imagery of the helicopter for both engineering confirmation of mechanism states and documentation of the process. On the final sol, the last deployment mechanism was released, dropping the helicopter to the surface. However, this meant the helicopter was now on its own electrical power and survival heating and needed to begin charging within 26 hours or it would not survive the following cold Martian night. The need to drive within a single sol is unusual for the rover as often operators can take their time planning drives or recovering from faults if a drive stops early. There are also many external factors that could cause a drive to take an extra sol such as a deep space network (DSN) outage, an orbiter going into safe mode preventing downlink, or an unrelated onboard fault that precludes driving. Thus, this critical nature of the drive off presented a risk to the successful deployment of the helicopter. RPs worked with HIEs prior to landing to plan the five meter drive off the helicopter to sequence it in a manner that ensured the highest likelihood of success. This included turning off error checking for a few systems that could have triggered false positive faults. Given that the drive was to take place on very flat, featureless terrain, it was decided to turn off thresholds for yaw and other suspension angle limits that are more important when the rover is traversing over uncharacterized, larger obstacles. An autonomous fault response was also included that would attempt to clear certain errors and reattempt the drive. However, given that the rover's health was critical to the prime mission, faults that could risk the rover such as mechanism failures were not cleared. Ultimately, the drive was a success and drove off the deployed helicopter without encountering any issues. The drop of the helicopter onto the surface began the 30 sol technology demonstration campaign.

The helicopter technology demonstration was proposed to take place across 30 sols, including checkout and commissioning, followed by up to 5 flights of increasing complexity and risk. The initial checkout included blade release, wiggles of the various mechanisms, a low-speed spin, and finally a high-speed spin. Throughout the initial commissioning, HIEs worked closely between the Helicopter Project and rover imaging operators to capture images and videos of these checkouts. The HIE team used RSVP to visualize planned imaging of the helicopter from the rover to ensure the proper pointing and framing [23]. Ultimately this same coordination was refined and reused for the initial flights, capturing the historic moment that the helicopter performed its first flight on sol 58 (April 19, 2021).

The typical flight cadence included a charge "hold" sol, a flight, followed by one to three transfer sols to send the logs, images, and detailed telemetry from the helicopter back to Earth. This entailed a number of data transfers from the helicopter to the helicopter base station (HBS) attached to the rover, into the rover's onboard memory, transmitted to an orbiter, then relayed back to Earth through the deep space network (DSN).

Following the success of the technology demonstration, the helicopter mission was continued in the capacity of an operations demonstration. During this phase, the helicopter scouted ahead of the rover, imaging areas of interest to help scientists select targets and for RP's to plan future drives. During this phase, the helicopter was no longer commanded every sol. Instead, operations transitioned into a cadence of completing a flight campaign across 4 sols, typically. First, a "capture" sol was planned which would catch the helicopter at a preset wake up time across three possible opportunities that the helicopter would wake up and listen for the HBS every sol. This capture sol would then set the helicopter heaters and alarms to enable a flight the following sol. Next, would be a flight sol commanding the helicopter to take flight and fly towards set waypoints capturing images with its return-to-Earth (RTE) color camera or greyscale downward facing NavCam. On this sol, the helicopter would only send back minimal telemetry to the rover indicating the status of the flight and the sizes of onboard files. Finally, one or two transfer sols would take place where the helicopter would send files--such as images, logs, and high-rate telemetry--back to the helicopter base station (HBS), then transfer from the HBS to the rover memory for downlink. Typically these products would be put at a lower priority and arrive on Earth during the next few sols as room was available.

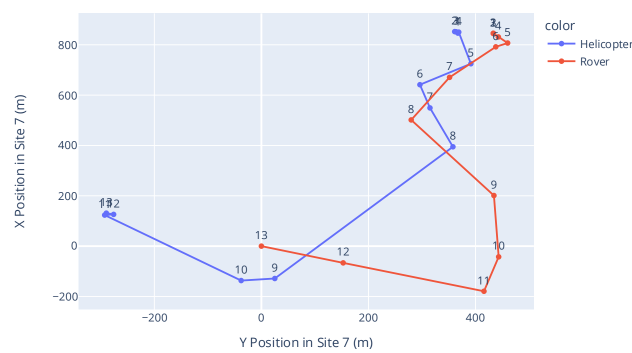

Figure 22: Helicopter and rover position at the start of each of the 13 flights through Sol 210.

Even after completing the initial 30 sol technology demo, the helicopter remained busy from sols 73 through 210 conducting 8 more flights—13 in total including the technology demonstration. shows the start and end location of all the helicopter flights through sol 210. These flights continued to push the limits of the system testing out higher altitudes (), faster speeds (Figure 24), and further distances (Figure 25) as the helicopter kept up with the rover's traverse towards the southern region of Seitah. Beyond sol 210, the Helicopter will continue to perform scouting operations for the rover while pushing the limits of its capabilities during seasonal lower atmospheric density.

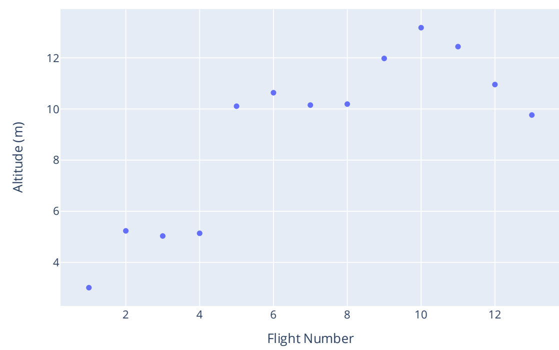

Figure 23: Helicopter altitude for each flight.

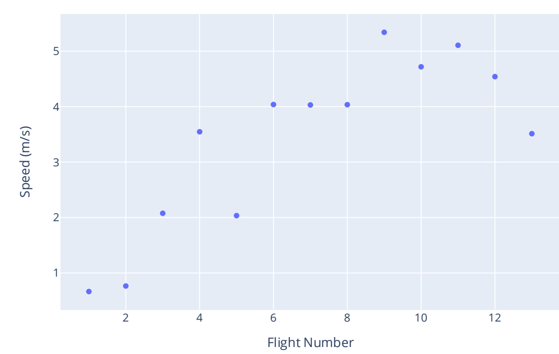

Figure 24: Helicopter speed for each flight.

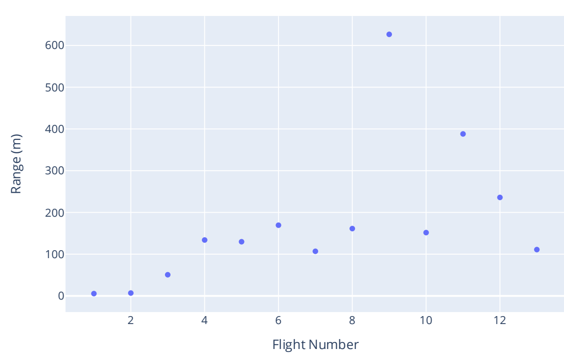

Figure 25: Helicopter horizontal range for each flight.

Visual Odometry and AutoNav navigation commissioning

During Perseverance's early mission, several sols were dedicated to commissioning the mobility system through first-time activities (FTAs). The FTA process is a workflow by which new complex capabilities are infused into Mars operations via a controlled scenario that allows for increased data collection and tightly constrained safety checks. After execution of an FTA on Mars, analysis of system performance and comparison to Earth-based testing is completed, before releasing the capability for unrestricted use by the operations team. This process exists out of an abundance of caution - some system behaviors (especially those involving hazard-avoidance driving) pose irreversible risk to the rover if the system malfunctions or is configured incorrectly, and the FTAs provide an opportunity to catch these issues before the behavior is officially deployed.

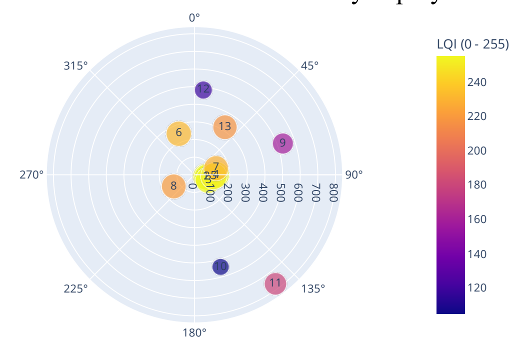

Figure 26: Helicopter and base station radio link quality indicator for each flight.

Nine FTAs were used to incrementally test aspects of the rover's mobility system: 3 FTAs dedicated to visual odometry (VO), 2 FTAs demonstrating onboard mapping, 2 FTAs running Guarded mode, and 2 FTAs running Avoid_All (AutoNav) mode. This series of mobility FTAs followed a two-step approach for each capability. First, behaviors were commanded in specific ways such that if they failed or produced invalid results, the rover would remain safe for the duration of the activity. For VO and Mapping, the initial checkouts were accomplished by running the algorithms and ignoring the results - VO pose updates were not pushed to the rover's SAPP (Surface Attitude, Positioning, and Pointing module) and the onboard heightmap generated by map updates was not used for hazard avoidance. Guarded driving was initially executed with reduced hazard height thresholds, causing small rocks in the terrain to appear as obstacles while in fact they were well below the mechanical safety limits for hazards. And AutoNav was first run across hazard-less terrain, with no obstacles to cause path deviations. There were also FTA-specific safety checks used that limited the drive length, suspension angles, and heading variation to tightly bound these initial checkouts.

During the second test of a behavior, the rover was commanded in a way that matched typical flight usage, but it was still done in a controlled scenario with extra safety checks. VO pose updates were integrated into the rover's pose estimate, which influences the drive path chosen towards Nav Goals. Nominal hazard thresholds were used for Guarded driving and a drive path was chosen to intersect with real mechanical hazards. For the final AutoNav test, the rover was commanded to drive to a waypoint on the far side of a large rock hazard, forcing the algorithm to choose a safe path around the obstacle. FTA-specific safety checks similar to the initial checkouts were reused to maintain a layer of safety that was tuned to match the known FTA scenarios. For example, in the AutoNav FTA around the large rock, the suspension limits were lowered such that if the front wheels started to climb the hazard, the rover would immediately stop driving. When these second "flight-like" FTAs completed successfully and performance was deemed to be nominal, the capability was then released for general operations across unknown terrain/lighting situations and forgoing extra safety checks. Note that while FTAs were employed to confirm that systems were working well on Mars, all of these capabilities had already been tested much more rigorously in Verification and Validation tests during mission development on Earth.

Visual Odometry became approved for general use on sol 100. Its ability to minimize position uncertainty allowed us to command longer drives, but we were still constrained to 30 meters max distance by the terrain meshes' ability to render obstacles in the right location.

Once AutoNav became available around sol 129, achievable drive distances increased dramatically. The science team chose multiple long-range goals for their observations, sometimes as far as 500 meters away. No longer constrained by meshes, it suddenly became possible to drive nearly 500 meters in just 5 sols, not 17 sols, and we quickly did so by sol 135.

Surface Attitude Position and Pointing propagation limit

Another operational constraint on drive distance has been the need to maintain the ability to point our High Gain Antenna to Earth to a certain precision. As we drive across the surface, the rover IMU accumulates an unknown (but bounded) amount of bias, which could result in inaccurate pointing if allowed to grow too much. Our SAPP ground operations team provides a maximum amount of on-time the IMU can accumulate before it risks accumulating more than the limit of pointing error. That constraint limits our drive distance as well. SAPP was also characterizing the IMU and slowly increasing that limit every few weeks. The latest increase is part of what enabled our record-setting drive on sol 200, 175 meters of total odometry across all drive modes.

Characterizing hazard mapping in sandy terrain

Finally, the remaining sols before solar conjunction (200-210) show lots of use of the Mapping mode without AutoNav taking advantage of it to select its own paths. These have been our first drives *inside* Seitah, and have had us driving over or near many small ripples. We are treading carefully through this terrain since similar ripples have caused difficulty for earlier missions (e.g., Opportunity got stuck for five weeks in Purgatory on sol 446, and Curiosity had to retreat out of Hidden Valley around sol 709 and Logan Peak around sol 984). So these initial drives have simply collected data we can analyze before we consider attempting AutoNav elsewhere inside the feature.

Robotic Arm First-Time Activities

As with mobility, robotic arm (RA) FTAs continue to be executed in parallel with the science mission resulting in a growing set of capabilities.

There were five RA FTAs during the first 200 sols. The first FTA performed a low standoff WATSON observation of the surface relative to an FCS touch. The FCS touch localizes the surface, eliminating most RA normal-vector placement accuracy uncertainty and errors in the stereo meshes used for planning. First the FCS is placed on the surface, and then WATSON is placed relative to the location where FCS detected contact. This style of placement has high heritage from previous Mars rover missions which relied on different contact sensors.

The second FTA conducted a similar observation; however the low standoff WATSON placement was planned relative to a higher standoff WATSON image acquired on a previous sol. WATSON's autofocus provides an accurate estimate of how far away the surface is from the imager. Additionally, lateral refinements can also be made by selecting a feature to target within the acquired WATSON image. While this technique takes two sols to execute, it offers a method to accurately place instruments when disturbing the surface with FCS is unfavorable. This approach is critical to observing abrasion patches and boreholes where disturbing tailings generated by the Corer is not desirable. Additionally, for cross contamination purposes, it is preferable to not touch FCS to surfaces intended for sample collection.

The third FTA, completed on Sol 125, performed low standoff PIXL and SHERLOC science observations. Surface localization was performed using PIXL's OFS. For scenarios when PIXL science will be conducted, PIXL's OFS provides an accurate and contactless surface measurement to use for targeting. After the completion of this FTA, natural surface science capabilities were fully available for use in the mission, while additional FTAs were required for abraded science, sample acquisition, and borehole science.

On Sol 159 through 162 the first abrasion and abraded science campaign was successfully executed, acquiring WATSON, SHERLOC, and PIXL observations targeted within an abrasion patch. Shortly thereafter, the first sampling activity took place on Sol 164.

SNC Commissioning and First-Time Activities

As of Sol 200, the sampling system is fully checked-out, in good health, and has collected two rock cores. Table 3 lists the key sampling activities so far, starting with functional tests and characterizations (through Sol 100) and moving into first-time activities and successful coring.

Sol	Activity
21	**Bellypan Deployment:** Fired pyros to drop ACA bellypan onto the Mars surface
24	**Bit Carousel Door Deployment:** Fired pyros to permanently open the upper- and lower- Bit Carousel doors

26	**Corer Functional:** Unstowed the Corer from its launch position and exercised all Corer actuators to characterize performance, which was successful and nominal.
87	**Docking Functional:** Successfully docked and undocked twice and characterized dock "seatedness", which was good. First time docking on another planet. **SHA Unstow:** Unstowed the Sample Handling Arm from its launch position
88 - 92	**ACA Functional:** Exercised and characterized all actuators in the Adaptive Caching Assembly. Required three attempts: first attempt faulted due to an overly-conservative thermal limit parameter, and second attempt faulted due to unreliable performance from a limit switch on the SHA linear stage.
97	**SHA Characterization Activities:** Successfully performed a set of characterization tests to measure SHA resolver hysteresis, linear stage backlash, and mechanism stiffness.
118 - 120	**Bit Carousel Witness Tube Processing:** Imaged, sealed, and stored a sample tube which witnesses the bit carousel contamination environment. Required two attempts, first attempt faulted due to a minimum-temperature thermal limit that was set too high.
142 - 147	**Corer Percussive Cleaning:** Removed contamination from the Corer by percussing in free-space and against a rock target. Required 4 attempts, first attempt faulted due to another thermal parameter limit, second and third attempts faulted due to a known motor-controller timing conflict.
148 - 150	**Launch Bit Dropoff:** Dropped off the Launch Bit Assembly (a modified abrading bit) by drilling a "cupholder" into a rock target, un-chucking the bit, and leaving it on the surface. Successfully performed first-ever bit exchange on Mars by picking up a clean new abrading bit.
160	**First full abrasion:** Abraded a rock target and removed dust from the abrasion using the gas Dust Removal Tool. Inspection of the abraded patch showed substantial voids in the rock.
164 - 167	**First sampling attempt:** Robotic operations completed successfully (a major milestone for the team) but there was no sample in the tube. Subsequent activities imaged the area around the rover and could not find the missing sample. Current hypothesis is that this weathered rock crumbled unlike anything previously observed in Earth testing with geoanalogs.
185	**Second abrasion:** Abraded and cleared target "Bellegarde" at a new sampling site. Visual assessment of the abraded rock, as well as drill telemetry, suggested the rock would be less "crumbly" than the prior sampling attempt.
189 – 195	**Second sampling attempt (first successful core):** Collected, sealed, and stored core sample from rock "Rochette". The activity was performed over several sols to allow ground teams to confirm the presence of a sample before sealing the tube.
196 - 197	**Third sampling attempt (second successful core):** Collected, sealed, and stored a second core sample from the same rock, this time in a single sol with no ground-in-the-loop.

Table 3: Key sampling activities in first 210 sols.

First 210 sols of Robotic Arm

RO executed multiple Robotic Arm activities in support of the science mission during the first 210 sols. The arm was unstowed 27 times (Figure 27), FCS contacted the surface 17 times and the drill was placed on the surface 9 times. The Corer was docked to the ACA 16 times (Figure 27), and WATSON, SHERLOC, and PIXL initiated their detailed science investigation of Jezero crater (Figure 28). WATSON, which was commissioned first and has the least stringent placement requirements saw the most use with 152 placements (Figure 28). SHERLOC was placed on 10 targets for spectroscopy observations. PIXL was placed for 8 observations. 3 rocks were abraded and 3 samples have been extracted and cached from 2 of those rocks.

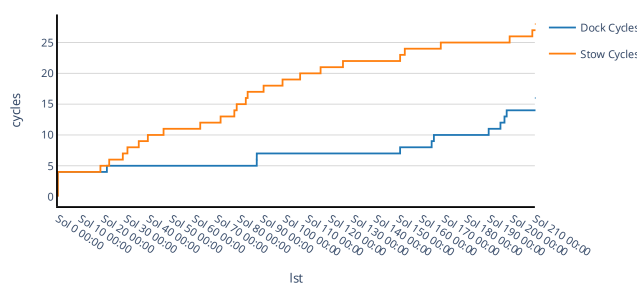

Figure 27: Robotic arm stow and dock cycles.

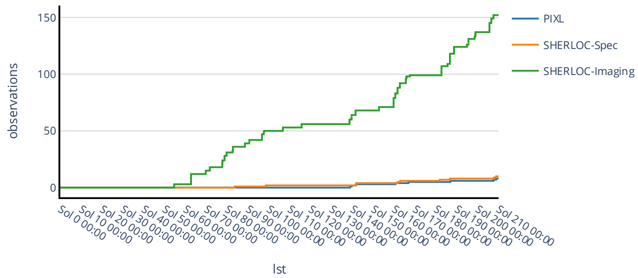

Figure 28: Robotic arm instrument observations.

9. LESSONS LEARNED

Perseverance is NASA's 4th generation Mars Rover. Many lessons learned from earlier missions have been incorporated into its design.

Value of rich simulation framework cannot be overstated

The VSTB Engineering Model [24] was scheduled to arrive late in development and expected to slip. The first complete VSTB that includes mobility, RA and sampling is planned for around Sol 250. Although flight software can be updated later in the mission, this has a significant impact on RO in early mission. Capability that is not ready results in a patch of workarounds and flight rule violations that can be difficult to check. The RO Flight Software development teams put substantial early effort into developing both software and hardware simulations such as SSDev [16], SSIM [17], Scarecrow rover [4] and QMDT [18]. These greatly reduced the number of issues discovered on the VSTB when it first became available for mobility testing. No prior mission had so many high-fidelity simulation support frameworks available early in its development.

Organizational structure has far-reaching impact

Robotic Operations is a new organization on Perseverance. Earlier Mars Rover missions organized their operations teams into two main categories: Uplink and Downlink. This resulted in Robotics specialists being split across teams. The Perseverance Project Management chose to create a third co-equal branch for its operations, the Robotic Operations branch. Not only has it enabled easier and more rapid collaboration across teams, streamlining the deployment of updates to operations tools and processes, it has also resulted in a vision and strategy that is in concert with the unique needs of robotics. Some areas of robotic operations have shifts that rotate through uplink and downlink.

Graphical commanding provides a better user interface

Perseverance is the first Mars rover mission to baseline Robotic operations sequence development in a graphical format. MobSketch, ArmSketch and macros enable RPs to interact with a graphical representation of the plan without typing commands directly, greatly increasing the speed of prototyping and refining plans in operations. Macros also help create safer sequences because they bound activity options, include built-in configuration and sanity checks, and contain expert-reviewed command strategies - all items which free-form or manually written commands would be missing. Furthermore, macros allow complicated sequences to be distilled into a handful of operator inputs, meaning that rover planners spend more time on design and safety review than typing commands. During these early Mars operations, the rover planners still review all commands generated by the macros, but eventually the team will transition to reviewing the graphical activity inputs alone, saving additional time during planning.

Operators design and develop an operable robotic system

In the flight community it is now well accepted that spacecraft need to designed with flight operations in mind. Requirements are specified with this intent. However, requirement are typically specified at a high level. There are numerous daily design choices designers and developers must make. Unless they have prior operations experience in robotics themselves or are co-located with others who do, the manner in which simple choices may negatively impact the high level intent can be missed. Almost all of the Perseverance robotics flight software developers had operated one or more previous rovers. Operations experience was represented across the board in robotic systems engineering, mechanical engineering and V&V as well. Rover Planner Subsystem (RPS) develops the ground tools used by RO. A number of the RPS developers have RO roles. Their experience with the user interface initiated MobSketch and ArmSketch.

Agile ground software deployment reduces errors

Ground software development in previous missions had traditionally followed a release cycle that is infrequent. But RO tool usage is almost continuous throughout the operations shift. When a ground tool error is discovered, it is far more efficient and less error prone to fix it in the prioritized order with a rigorous test and release process, rather than wait for a fixed next release cycle. There is a nightly build used for testing, a stable build that may be used for strategic work, and a released version used for tactical operations. Perseverance is the first Mars rover mission where this strategy is part of the official RPS tool delivery process.

Benefit of Operations tools for Verification & Validation

Due to the high heritage from Curiosity a lot of the operational tools had early prototypes. Operations experience on the V&V team meant they were aware of the potential in these tools. Dedicated resources were invested earlier in the tools. This served multiple purposes. It improved the ease and efficiently of verification and validation, provided early feedback on tool development, and trained operators.

AutoNav eliminates viewshed planning concern

Perseverance AutoNav is both more capable at traversing challenging terrain (i.e. allows the rover to straddle rocks) and drives much faster than its predecessors (~5x faster and nearly as fast as human-directed driving). Thus almost the entirety of the strategic route developed so far relies on AutoNav driving, assuming 100-150m of drive distance per sol on average, depending on terrain complexity. With past rovers the strategic route would be highly dependent on the viewshed of the rover navigation cameras (NavCams) at the end of each drive, as human-directed drives are limited to driving on the mesh generated from post-drive imaging. That is no longer the case with Perseverance where the main driver of the traverse rate is now the duration that can be allocated for driving, which is limited by other planned activities (i.e., pre-drive remote science) and timing of the orbiters' communication passes that allow for transmitting the rover data back to Earth (i.e., a drive can be shortened by an early decisional pass). The longest distance driven with AutoNav so far in a single sol was 167 m, on sol 200, but we expect greater distances in the near future as more time is allocated for driving in order to reach the Delta as quickly as possible once the sampling campaign is over.

Mobility updates increased AutoNav usage

Earlier missions experienced a significant slowdown in overall drive rates when autonomous imaging was enabled due to multiple factors, including stopping to acquire images, requiring mast slewing to achieve sufficient image field of view, and stopping to process images before selecting the next step. To achieve higher capability mobility requirements on M2020 several architectural changes were made to enable faster autonomous driving. Neutral density filters on cameras were removed to enable faster exposure times (5 ms vs 250 ms), enabling acquisition of images while literally in motion. Mast camera field of view was widened enough to eliminate the need to slew on nominal drives. And additional VCE/FPGA computing resources were added to speed up processing of image data. This has improved Visual Odometry speed to an extent that there is no appreciable reduction in drive speed from using VO. There is in fact a noticeable *increase* in drive rate after we VO was commissioned. It also significantly reduced drive planning complexity since rover drivers didn't have to factor in what-if scenarios for slip the onboard system could not account for without VO, even on a new rover that was still being characterized on Mars. Prioritizing VO commissioning so it is available earlier in the mission timeline has value. In addition to the hardware improvements, the onboard Mobility Flight Software architecture was updated to support faster drive rates during autonomous mobility via *Thinking While Driving*. Instead of stopping to wait for the latest image processing results as prior missions did, Perseverance now starts executing the next step before the new image results are available. That, in combination with the new Arc Blending capability, enables continuous motion so long as the vehicle doesn't change its arc curvature (which would require stopping to re-steer due to the limited number of motor controllers) [19].

Automated checks eliminate Visual Odometry errors

Visual Odometry has proven invaluable for robotic operations on Mars, allowing rover drivers to compensate for slip in the oft encountered sandy terrain, ripples and dunes. So far Perseverance has not encountered a single VO failure on Mars. Automated command expansion via macros ensures careful strategic oversight of potential causes of error such as insufficient overlap between VO images. Flight software in the loop simulation using SSIM [17] and automated rule checkers allow checking for shadows and catch state interaction violations.

Position Uncertainty simplifies AutoNav operations

Prior rover missions have only had to plan drives on the scale of 100 meters or so, rarely venturing into multi-sol autonomous drives due to the resource-intensive (and slower drive rate) AutoNav capabilities on those missions. But the Mars 2020 mission requirements added the need to plan for potentially 500 or more meters of driving per command cycle to meet to meet sampling and distribution goals over the life of the mission. At those scales even the fine 1-2% precision of position knowledge attainable with Visual Odometry can result in over 10 meters of position uncertainty at the end of a drive. That makes it very challenging for Rover Planners to adequately specify Keepout Zones around non-geometric hazards hundreds of meters away. On past missions, Rover Planners have had to estimate the rover position uncertainty and manually grow each Keepout Zone by the worst-case uncertainty. But the Perseverance flight software now incorporates an onboard uncertainty model, new to Mars 2020. Uncertainty is modeled as a disc, and it grows with the odometry accumulated by the rover since the last place that human Rover Planners evaluated the nearby terrain. Keepout Zones are laid out based on nearby NavCam and far-ranging orbital imagery, and their accuracy depends on how well-localized those maps are to the current position. As Perseverance drives, Keepout zones are automatically grown by the current onboard uncertainty amount. That will help ensure that any hazards identified by Rover Planners will never be encountered by the vehicle, even if they were specified hundreds of meters away from where the rover started. As such, the Keepout zone growth is conservative and hence there are challenges with using AutoNav to thread a needle between hazards.

Expedited sampling with Adaptive Caching Assembly

Decoupling the robotic arm and sample processing by incorporating a second robotic system, the ACA, has improved efficiency and reduced complexity as compared to the sampling architecture on Curiosity. It has allowed having a separate Sampling and Caching operations planning team and not restricting robotic arm usage for an extended period of time during sample processing. Once the arm docks and tube transfer is confirmed the two pathways can continue in parallel.

Strategic Product Design Enabled Efficient Sampling

As highlighted in Figure 9, using the sampling system to perform abrading and sampling activities requires hundreds to thousands of sequential commands, depending on the complexity of the activity. These operations have been developed over the course of years of testing [20]. Each mechanism motion, parameter adjustment, and state change is essential to successful operation. Most of the commands are the same for each coring, abrading, and sample processing activity, with only a few arguments and parameters which change tactically. The majority of SNC commands are delivered in strategically-developed sequences and SPAM scripts (a special binary file containing a list of commands, which can itself be executed like a regular command) [21]. These strategic sequences and SPAM scripts are rigorously change-controlled and tested, reviewed, and simulated at multiple steps. Additionally, they are generally uplinked to the vehicle ahead of use and stay onboard until replaced with a newer version, which reduces uplink data volume. SNC operators do not edit these products tactically. SNC operators deliver tactically-generated sequences for the handful of arguments and parameters which do necessarily change each time. These sequences include commands to choose specific drill bits and sample tubes, adjust parameters for rock hardness and abrasion depth, and specify gDRT valve durations (which depends on temperature). For the most part, these tactical sequences are generated via macros, where the SNC operator inputs arguments to a script which generates the sequence. In the case of off-nominal operations including fault recovery, SNC operators can manually edit these sequences. A typical sampling operation, including docking, bit exchange, sample acquisition, and sample processing uses over a hundred products. To collect a recent core sample on Sol 196, SNC used 27 SPAM Scripts, 73 Strategic Sequences, and 11 Tactical Sequences.

Strategic Route Plan

There were plans to rely on a new automated tool, called Mars Terrain Traversability analysis Tool (MTTT) [22] for generating the strategic routes. The science team was planning to use this tool directly and only consult the RPs for blessing the chosen routes, after multiple iterations within the science team depending on the duration estimates provided by MTTT for the various routes considered. But it was discovered that MTTT routes were often unrealistic and infeasible for the rover to drive. For example, the route generated by MTTT to reach the Delta from the landing site would have had the rover go straight through Séítah, driving through seemingly untraversable dune fields to get there. The process was quickly updated to instead have the science team provide the RPs with the desired destinations (science targets) and let the RPs do the strategic route planning by leveraging their experience. While an automated tool for assisting RPs with strategic route planning would be nice to have, in practice more advances are still needed in automated route evaluation in orbital maps.

Nice to have a scout helicopter

We learned that the Ingenuity helicopter was capable of scouting ahead of the rover and could provide useful imagery for informing the strategic route of the rover and traversability of the terrain. In particular the Return To Earth (RTE) images taken by Ingenuity during Flight #12 of Southern Séítah, illustrated in Figure 6, not only helped the Science team decide whether it was worth driving to that destination in the first place, but it also helped the RPs gain more confidence in the traversability of the planned strategic route through that area and make small adjustments to it ahead of time based on the higher-resolution helicopter imagery.

10. CONCLUSIONS

The Mars 2020 mission has had an outstanding first 210 sols. And the Robotic Operations team has managed successful demonstrations and continued use of many complex and novel robotic capabilities: the first interplanetary aerial robot completed 13 flights on another world; AutoNav has driven faster, more frequently, and farther in one sol than any prior rover; single-sol autonomous Sample Caching has been performed for the first time on an interplanetary mobile platform; and more. Making Robotic Operations an independent organizational branch has led to remarkable operational milestones. We look forward even more ambitious ones in the years to come.

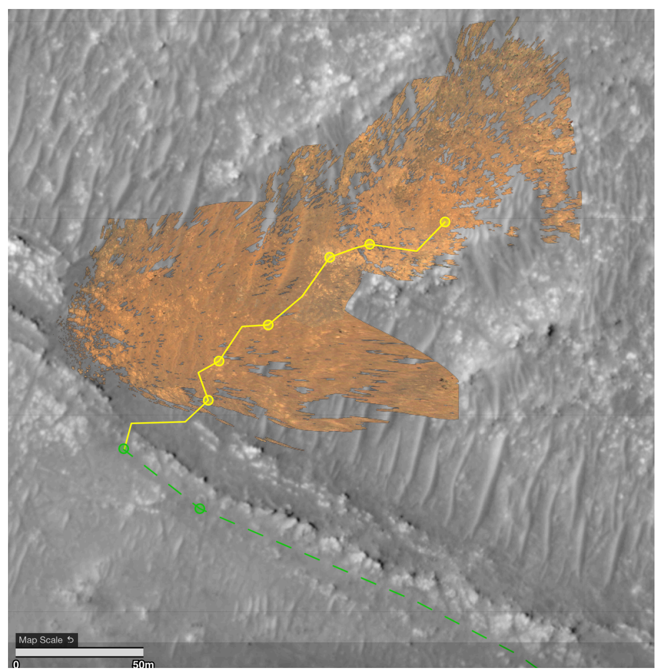

Figure 29: Color images taken by Ingenuity overlaid over the planned strategic route of the Perseverance rover. The much higher resolution (images were taken 10m above ground) was very helpful to both the Science and RP teams for planning the Séítah toe dip.

ACKNOWLEDGEMENTS

The research was carried out at the Jet Propulsion Laboratory, California Institute of Technology, under a contract with the National Aeronautics and Space Administration (80NM0018D0004). The authors would like to thank the M2020 operations and development teams for their support and contribution, particularly the Robotic Operations, Rover Planning Subsystem, and Strategic Sampling Operations team members.

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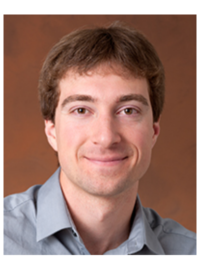
BIOGRAPHY

Vandi Verma *is the Chief Engineer of Robotic Operations for Mars 2020 Perseverance and the Deputy Manager for Mobility and Robotic Systems at NASA JPL where she leads about 150 roboticists. She holds a Ph.D. in Robotics from Carnegie Mellon University and specializes in autonomous robots and robotic operations. She has worked on the Mars Exploration Rovers,* *Curiosity rover, Perseverance rover, Ingenuity helicopter technology demonstration, Europa Clipper Autonomy Prototype, Europa Lander, and autonomous research robots in the Arctic, Antarctica and Atacama. She works on new robotics capabilities from early design through development, testing and launch, to landing and surface operations.*

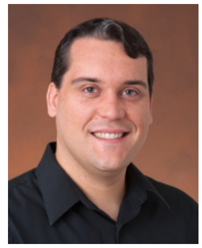
Frank Hartman *is one of the original authors of the RSVP software which was created in 2000 in support of the Mars Exploration Rover mission based on earlier work for the Mars Pathfinder mission. Frank was also selected as one of the original eight rover drivers for that mission - driving the Opportunity rover for 7 years before transitioning to the MSL mission and becoming the lead rover driver there. Currently serving as the Robotic Operations Team Chief for the Mars 2020 mission, Frank holds a Bachelor of Fine Arts degree in Sculpture from the University of the Arts and a Master of Science degree in Aeronautical and Astronautical Engineering from Stanford University.*

Arturo Rankin *received his Ph.D. in Mechanical Engineering at the University of Florida in 1997. He is currently a Robotic Systems Engineer in the Robot Operations group at the Jet Propulsion Laboratory, and the M2020 Robot Operations deputy lead. Prior to that, he was the MSL Mobility/Mechanisms team lead and the MSL Flight Software team lead.*

Mark Maimone *is a Robotic Systems Engineer in the Robotic Mobility group at the Jet Propulsion Laboratory. Mark designed and implemented the GESTALT self-driving surface navigation Flight Software for MER and MSL missions; during MSL operations served as Deputy Lead Rover Planner, Lead Mobility Rover Planner and Flight Software Lead; developed downlink automation tools for MER and MSL; and is now the Mars 2020 Deputy Lead Rover Planner and a member of the Rover FSW development team. He holds a Ph.D. in Computer Science from Carnegie Mellon University.*

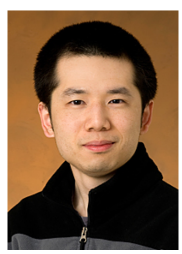


Tyler Del Sesto *received his M.S. degree in Mechanical Engineering from Carnegie Mellon in 2016. At JPL, Tyler's work focuses on control and testing of mobile robots and improving operability of robotic spacecraft. He was the test lead for Mars2020's autonomous driving software during development, and a mobility systems engineer during integrated systems testing. Tyler served as a robotics operator of Curiosity rover for four years, and is currently an operator and mobility domain expert for Perseverance rover.*



Olivier Toupet *received his M.S. degree in Aeronautics and Astronautics from MIT in 2006. He is currently the supervisor of the Robotic Aerial Mobility Group at the Jet Propulsion Laboratory, which develops innovative technologies for UAVs with a focus on guidance, navigation, and control. Mr. Toupet has several roles on the M2020 project, including deputy lead of the Rover Planner team, lead of the Strategic Route Planning team, deputy lead of the Helicopter Integration Engineer team, and lead of the Enhanced Autonomous Navigation Flight Software team.*

Evan Graser *is a Systems Engineer in the Engineering Operations for Surface Missions group at JPL. He is a Mobility downlink engineer for Mars 2020 and is the Mobility & Mechanisms subsystem team lead for MSL. He is also a member and lead trainer of the MSL Engineering Operations Systems team. Evan received is MS in Aerospace Engineering from the University of Colorado, Boulder.*



Steven Myint *is the group lead of 347K in the Robotics section of the Jet Propulsion Laboratory. His recent work include developing flight software for the Mars 2020 rover, applying modern software fuzzing techniques to finding problems in safety-critical flight software, and leading the development of SSim (Surface Simulation), the primary simulation tool for Mars 2020 rover operations.*

Kevin Davis *received a B.S. (2010) and M.S. (2015) in Aerospace Engineering from the University of Maryland. Kevin joined JPL in 2015, working primarily in operations and systems engineering roles for the Mars Science Laboratory and Mars 2020 projects, with a focus on the robotic arm subsystem on both projects. They currently serve as the deputy lead for the Mars 2020 Robotic Operations Downlink Team, and also serve as a Rover Planner for the Mars Science Laboratory and Mars 2020 rovers.*

Douglas Klein *received a B.S. in Aerospace Engineering from the University of Maryland in 2014 and an M.S. in Astronautical Engineering from the University of Southern California in 2018. He has performed several roles on the Mars Science Laboratory and Mars 2020 teams, primarily focusing on robotic and sampling systems engineering. He is the lead systems engineer for the Robotic Arm on Mars 2020.*

Justin Koch *received his B.S. in Mechanical Engineering from the California Institute of Technology. Justin is a robotics engineer in the Robotic Actuation and Sensing group at the NASA Jet Propulsion Laboratory. His research focuses on underwater and other extreme environment robotic systems as well as Mars operations. Justin has worked on a variety of robots, from an underwater AquaSimian robot arm to an under-ice buoyant exploration rover that explores polar regions. He has previously served as a Rover Planner for the Curiosity rover and is currently a Rover Planner for the Perseverance rover, as well as the Lead Helicopter Integration Engineer for the Ingenuity Mars Helicopter.*

Sawyer Brooks *received his B.S. and M.S degrees in Mechanical Engineering and Robotics from the University of Pennsylvania. He is a Robotics Systems Engineer at JPL with a focus on testing and operating complex robotic systems. He has worked in a variety of roles on the Mars 2020 Sample Caching Subsystem including as the Deputy Lead for Testbed Software, the Deputy Lead for Sampling and Caching Uplink Operations, and the Docking Systems Engineer.*

Philip Bailey *received his B.S and M.S in Electrical and Computer Engineering from Carnegie Mellon University both in 2014. He joined JPL in 2015 where he has worked on several flight missions. He was a systems engineer, robotic arm planner, and eventual robotic arm surface operations load for InSight. On M2020 he was a systems engineer for the Robotic Arm and lead the robotic arm commissioning after landing.*

Heather Justice *received her B.S. in Computer Science from Harvey Mudd College and M.S. in Robotics from Carnegie Mellon University. She has worked at JPL since 2011 focusing on spacecraft operations. She is currently a member of the Mars 2020 Perseverance operations team as the Robotic Operations Downlink Team Lead and as a Rover Planner. She also previously performed numerous roles for the Mars Exploration Rover operations team including Rover Planner Team Lead during the last few years of Opportunity's mission.*

Marco Dolci *joined the Robotic Vehicles and Manipulators Group in 2017 working as Robotics Systems Engineer on flight projects. Dr. Dolci received his Ph.D. from Politecnico di Torino in Aerospace Engineering on Space Exploration Robotic Systems - Orbital Manipulation Mechanisms in collaboration with Thales Alenia Space Italy and NASA JPL - Caltech. He received a MS in Space Engineering, and has experience in space systems, orbital mechanics, attitude determination and control systems, space environment, payloads, and CubeSats (TeamXc experience). Dr. Dolci received also a BS and MS in Physics with experience in data analysis, antennas, optics, cosmic rays and astrophysics.*