Perseverance Rapid Traverse Campaign

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Abstract—**Over the first 13 months of the Mars 2020 mission, the Perseverance rover traversed nearly 5 km along the Jezero Crater floor. Near the end of that period, the Science team was anxious to relocate to the ancient Delta region near the crater rim, over 5 km away. A Rapid Traverse Campaign was planned that would prioritize use of Perseverance's autonomous navigation software to drive at an unprecedented high pace and minimize science activities. The Rapid Traverse Campaign started in March 2022 and lasted 31 Martian days. During the campaign, Perseverance drove over 5 km in 24 drives, during which its autonomy software planned 94.8% of its overall driving, enabling it to set several new planetary rover driving records. Perseverance exceeded the longest daily drive distance record achieved by a previous planetary rover (219 meters) 11 times and set new records for the longest multi-sol drive distance in a single plan (528.7 meters) and the longest continuation drive (699.9 meters) by operating without human drive path input during 3 sols of driving. This paper details the planning and execution of the Rapid Traverse Campaign.**

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1. INTRODUCTION

On February 18, 2021, the NASA Mars 2020 (M2020) Perseverance rover successfully landed on Mars in Jezero Crater. To ensure a safe landing, terrain relative navigation [1] diverted Perseverance a few kilometers away from the Delta, a primary mission site for collecting samples, to the east of a ripple field called Seitah (see Figure 1). Over the first 98 sols of the mission, Perseverance completed a surface operations commissioning phase to establish rover and helicopter health, safety, and operational characteristics prior to the start of nominal operations [2]. Perseverance drove 4,927.8 meters during the first 13 months of the mission while checking out subsystems and performing science in the vicinity of the landing site and south of an area designated as Seitah, which contains numerous sand ripples [3]. During this exploration, a Rapid Traverse Campaign was planned to drive as quickly as possible to the Delta primary mission site once the South Seitah campaign had completed. Driving would take priority over new science observations for the duration of the campaign.

Preparation for Rapid Traverse included modifications to the Operations tactical timeline, reduced science staffing, a restriction on allowable activities to maximize available drive time, deployment of an additional drive mode, and updates to ground tools and onboard command sequences. Strategic route planners generated two candidate routes to the Delta, one through the ripple field and a 4.8 km route around the north side of the ripple field. Although the total length of the route through the ripple field was shorter, it would require more drive sols with a higher risk of drive faults due to the need to drive through the as-yet-unexplored sand ripples. The route around the north side of ripple field was selected by the project and the Rapid Traverse Campaign commenced on sol 379 and completed on sol 409.

Over the 31 sol campaign, 27 drives were planned. Of the 27 planned drives, 24 were executed, two did not execute due to onboard anomalies, and one did not execute because it was not uplinked to Perseverance due to a ground tool issue. During the one-month Rapid Traverse Campaign, Perseverance drove 5,063.4 meters, exceeding the odometry achieved over the previous 13 months. In addition, several Mars rover odometry records were set during the Rapid Traverse Campaign. The longest multi-sol drive distance in a single plan (528.7 meters) was achieved over sols 404-405 and the longest continuation drive distance (699.9 meters) was achieved over sols 407-409. In addition, 11 of Perseverance's drives during the campaign were longer than the longest drive achieved by any previous Mars rover (219 meters by Opportunity in 2005).

In this paper, we provide some historical context to this unprecedented high-pace drive campaign and describe the updates made to Mission Operations, tool and sequence development, modes of driving, strategic route planning, day-to-day drive planning, and mobility downlink assessment, which all contributed to the success of the Rapid Traverse Campaign.

2. HISTORICAL CONTEXT

Perseverance is NASA's 4th generation rover, with its predecessors being Mars Pathfinder (MPF) Sojourner, Mars Exploration Rovers (MER) Spirit and Opportunity, and Mars Science Laboratory (MSL) Curiosity. The sizes of the Curiosity and Perseverance rovers are nearly identical with

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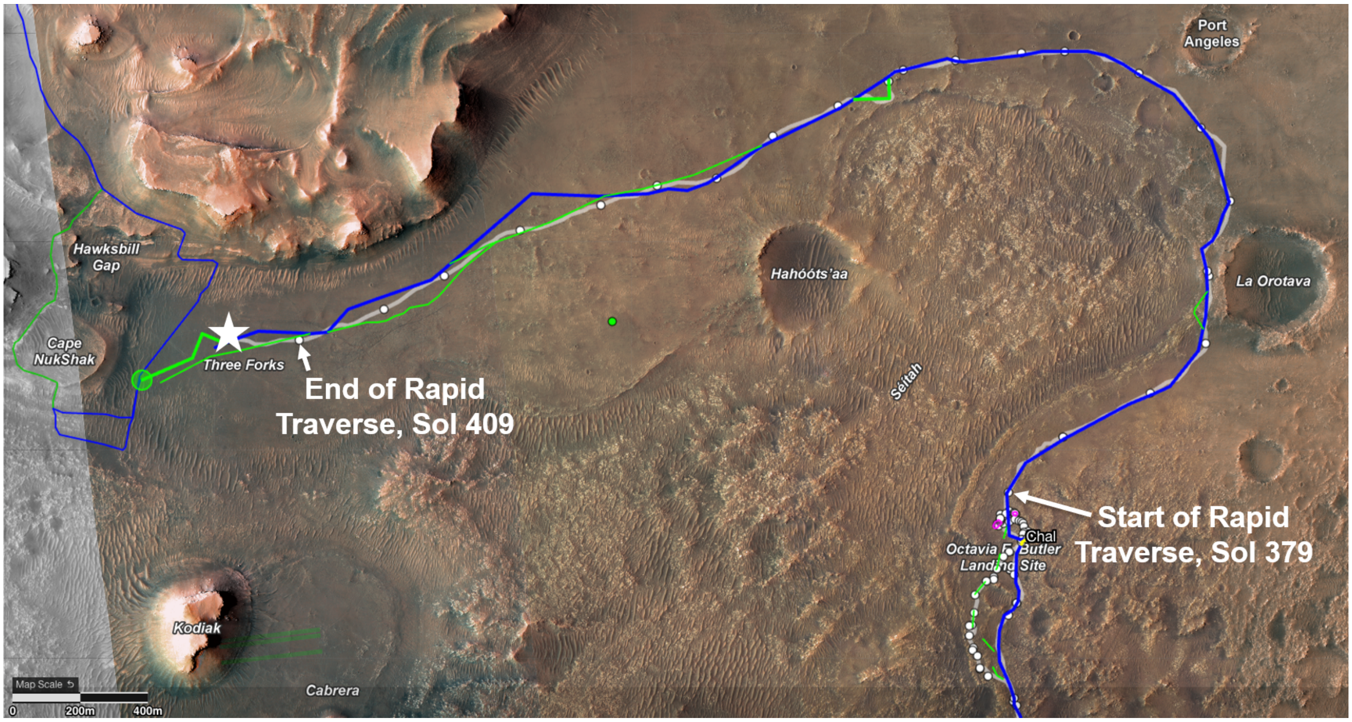


Figure 1. The originally planned strategic route is in blue, a refined strategic route is in green, and the actual rover route is in white. The Rapid Traverse Campaign began near the Octavia F. Butler Landing Site on sol 379 (March 14, 2022) and ended on sol 409 (April 14, 2022) next to the Delta area in the northwest, after traveling over 5 km around the edges of the Seitah area. The white dots indicate the rover position at the end of each Martian solar day.

Perseverance being 126 kg heavier. Perseverance's mobility system design and capabilities are described in [4].

Every NASA rover has had some capability for autonomous driving, even Sojourner [5], [6] which drove 104.3 meters during its mission. And each NASA rover mission has improved on the prior missions' autonomous imaging and mobility capabilities along one or more dimensions. The MER rovers had a main computer (Rover Compute Element, or RCE) that was 10X faster than Sojourner, drove more than 10X faster, and processed 1,000X as many pixels measuring the terrain during autonomous driving [7]. The MSL RCE was over 6X faster than MER, processing 4X as many pixels with 4X the RAM and 16X the non-volatile storage [8]. Perseverance now has two MSL computers (one RCE and one Vision Compute Element, or VCE; both are RAD750 boards). The VCE also includes a Virtex 5 FPGA for onboard image computation for Visual Odometry and Stereo Correlation algorithms, processing 6X as many pixels per step as MSL in much less time. Table 1 summarizes the changes in onboard autonomous computing capability for all the NASA Mars Rover missions thus far.

For the first time, a NASA Mars Rover's overall autonomous driving speed is not limited by sensing or computing time, but rather by rotation rate of the wheel drive motors. Like the MER and MSL rovers, the maximum drive speed of 4.2 cm/s on Perseverance is the result of fixed gear ratios chosen to maximize climbing capability rather than speed [8]. The faster computing and improved Thinking While Driving software design on Perseverance [9] enable the use of both Visual Odometry and Hazard Avoidance at speeds nearly the same as purely human-directed drives, unlike earlier rover missions that were forced to drive as much as 4-10X more slowly overall whenever autonomous driving was enabled [8]. This enhanced capability has allowed us to take advantage of autonomous navigation (Autonav) in an unprecedented way. On earlier missions, Autonav was typically used as a drive extender, a way to travel tens of meters into unknown areas at the end of a human-directed drive through nearby known terrain [10]. But as described in this paper, our operations team is now able to routinely plan hundreds of meters of driving each sol, the great majority of it being driven autonomously.

Autonav terrain analysis only has a geometric understanding of the terrain, so it is still incumbent on the Rover Planner (RP) team to manually specify any non-geometric hazards or other "keep out " areas the rover might encounter along the way (such as targets of scientific interest, potential sand traps, sample tubes or helicopters). But the Rapid Traverse strategy described in this paper is most notable for flipping the percentages. In the MER and MSL missions, Autonav drives also kept the rover safe in unknown areas, but were only selected for use during less than 7% of all driving overall. In contrast, during Rapid Traverse, over 94% of all driving was done using full onboard autonomy, including fully enabled Visual Odometry, and Hazard Detection and Avoidance.

The Perseverance Rapid Traverse Campaign is thus notable for both the cumulative odometry achieved in 31 sols and also the amount of odometry that was achieved using Autonav. As shown in Table 2, Perseverance achieved more than twice the odometry achieved by any previous NASA Mars rover over a 31 sol period. And as shown in Table 3, Perseverance achieved over 5 km of odometry in fewer than 1/3rd of the number of sols required by any previous NASA Mars rover.

Perseverance achieved 4.3 times more odometry in Autonav mode during the 31 day Rapid Traverse drive than Curiosity

Table 1. Evolution of NASA Mars Rover Onboard Autonomy Specifications

Category	Sojourner	Spirit and Opportunity	Curiosity	Perseverance
Landing Year	1997	2004	2012	2021
CPU	80C85	BAE RAD6000	BAE RAD750	BAE RAD750 (2x), FPGA Xilinx Virtex5QV
MHz	2	20	133	133 (x2) + FPGA (22M disparities/sec)
RAM (Mbytes)	0.56	128	128 + 512	128 (x2) + 512 (x2)
Non-volatile storage (Mbytes)	0.17	256 flash	4,096 flash	4,096 + 3072 flash
Image Pairs / Step	1	1-2	4	1
Stereo Pixels processed per step	20	10,000 - 50,000	40,000 - 200,000	FPGA: 240,000 - 1,200,000
Autonav Pause per step (seconds)	*unknown*	c. 120	c. 120	typically 0 if not steering

Table 2. Maximum NASA Mars rover odometry over a 31 sol period.

Mars Rover	Sols	Max Odometry
Sojourner	12-42	68.7 m
Spirit	104-134	1,725.6 m
Opportunity	393-423	1,906.2 m
Curiosity	642-672	1,552.6 m
Perseverance	379-409	5,063.4 m

Table 3. Minimum number of sols NASA Mars rovers have required to drive 5 km. Sojourner is not included since it drove less than 5 km during its mission.

Mars Rover	Min # of Sols	Sol Range	Odometry
Spirit	594	44-638	5,004.1 m
Opportunity	96	2575-2671	5,066.1 m
Curiosity	240	332-572	5,012.8 m
Perseverance	31	379-409	5,063.4 m

has during 10.5 years of surface operations on Mars to date. The use of Autonav by Curiosity, which was documented after 7 years of operation on Mars in [8], has been limited by multiple factors, including the discovery of physical wheel damage [11], and science mission sampling priorities. As of the end of the Rapid Traverse Campaign on April 14, 2022, Curiosity has achieved 1,116.7 meters of total cumulative Autonav odometry. In contrast, Perseverance achieved 4,802 meters of Autonav odometry during the one month Rapid Traverse Campaign alone.

China's Zhurong Mars rover landed on Utopia Planitia in May 2021, and has been exploring the Martian surface ever since. Detailed traverse information is available for its first 60 sols of operations, during which it drove a total of 450.9 meters [12]. They report a nominal commanded velocity of 5.6 cm/sec, their slip-corrected data show a mean and median velocity of 5.13 cm/sec, ranging from 2.24–5.83 cm/sec, and they report per-sol traverse distances ranging from 0–20.7 meters on any given sol with mean 12.2 meters and median 10.8 meters.

Zhurong has an ”autonomous obstacle avoidance movement mode” [13], and information about the onboard stereo vision processing is described in [14]. That same paper describes the daily strategy of an initial human-directed drive followed by autonomous driving, which was capable of achieving up to 20 m/sol over the first approximately 1 km traversed during a 100 sol period. They also report a maximum autonomous distance of 15.12 meters in a single sol over that period, with autonomous driving being responsible for more than 40% of the total drive distance overall.

3. MISSION OPERATIONS

During the Spring of 2022, the M2020 team augmented their flight and ground processes to enable a Rapid Traverse Campaign to be used during Perserverance's record breaking drive to Jezero Crater's Delta. It was specifically designed with this campaign in mind and not meant to be used for nominal mission operations. This was because the M2020 tactical processes and tools were already continuing to improve and optimize and evolve as the team learned on Mars, and it was unknown when we would be doing another long drive campaign of this kind during our mission.

While planning out the South Seitah Science campaign the Science leadership, aware that every sol on Mars is a commodity, recognized that a temporary decrease in science activities was necessary to accomplish mission goals. Early on, the project decided the focus and priority was to get to Jezero Delta as quickly as possible. The project stood up a weekly working group with key leadership, system engineers, and representatives from the Engineering Operations, Robotic Operations, Instrument Operations, Science Operations, and Ground Data System teams. Its charter was to figure out how to maximize drive distance during Rapid Traverse.

The team drew inspiration from a similar campaign that was done on MSL back in 2014. The team brainstormed ways to maximize drive time on Mars and wrote down all the geometric and flight system constraints that limited the time and duration of driving. The team also streamlined the surface tactical planning timeline to be shorter and more efficient during this period. This was beneficial because a shorter tactical planning day meant the project could increase the number of ground in the loop planning cycles, allowing the team to be more reactive and respond to what we see on Mars (i.e., analyze and review the Martian terrain, respond to a drive fault, etc). The key elements that led to increased drive time during this period were (in order of most beneficial from top to bottom):

1. Multi-sol Autonav capabilities increasing the number of drive legs that can be planned with fewer ground in the loop planning sessions.
2. Reduction of science and instrument activities. Limiting the duration and number of science blocks during the campaign to enable more drive time and power.
3. Optimizing engineering activities to increase drive time. The Operations team implemented a number of changes to gain more drive time, like redesigning some low-level sequences to be pulled out and be put after the drives, deprioritizing certain comm activities during this period (i.e., Beeps) and shortening and optimizing post-driving imaging activities, and allowing certain activities to be executed in parallel.
4. Simplifying Operations processes and staffing to enable a shorter planning timeline

The Operations team worked out an agreement early with Science leadership to limit science activites during the campaign, which helped pave the way to work on the lower-level details and more engineering trades, rather than focus on science vs. engineering trades. Specific engineering items that were enabled during this period were:

1. Simplify the ability for the engineering team to move data management deletes and VCE imagery transfers later in the sol after the drive.
2. Allow the team to execute ”Honks” instead of ”Beeps” where we allow driving in parallel with a Low Gain Antenna carrier session with Earth.
3. Reduction and streamlining of the Post-Driving Imaging (PDI) including customization for multi-sol drives

It should also be noted that in parallel with this development, all the teams were also working on lower level improvements to their operations procedures, tools and scripts in support of Rapid Traverse. As the Rapid Traverse Campaign neared, the team was not able to complete everything that was on the list, but did complete the highest priority items. About 3-4 weeks prior to the start, following the standard process on how to communicate updates to processes and staffing to the flight team, the Operations system engineers and team leads updated flight documentation and created a flight school to educate the team on what would be changing, as well as a briefing on the newer drive capabilities being rolled out. This method proved to be a good lightweight way to get updates completed in a timely manner and train the flight team in a short amount of time.

4. TOOL AND SEQUENCE DEVELOPMENT

The Robotics Operations (RO) team is responsible for the driving, manipulation, sampling, and helicopter portions of Perseverance's daily operations [3]. The RO team recommended and implemented several tool and process updates in support of the Rapid Traverse Mission Operations changes described in the preceding section.

Autonomous Attitude Correction

The rover must maintain a reliable knowledge of its attitude in order to maintain the ability to communicate directly with Earth using its High Gain Antenna. It nominally uses gyros to integrate attitude changes at high rates while in motion, but that process accumulates error over time. Once a conservative bound on that error grows beyond a specified threshold, an attitude update activity must be performed to reset the onboard attitude knowledge [15]. Each such update eliminates the accumulated heading uncertainty via an absolute heading measurement using onboard Sun-finding image processing software that records the new measurement for future use.

Prior to Rapid Traverse, most such updates were scheduled and sequenced by hand. But long autonomous drives could require multiple such updates within a given multi-sol plan. So a new strategy was incorporated into the macros, enabling the rover to autonomously detect and respond to the need for a new Attitude Update either during an autonomous drive, or after the drive had ended. The strategy only supported a single such update per individual drive segment, but could be repeated over any number of drive segments.

Sequencing and Macro Updates

Perseverance's mobility activities are typically planned using the MobSketch graphical user interface provided by the Rover Sequencing and Visualization Program (RSVP) [16]. Graphical elements are used to draw a sketch of one or more sols of activities, and the parameters of those graphical elements are fed through strategically developed macros to create a complete sequence of commands needed to drive the rover. Whereas in prior missions human RPs had to create, review and maintain these command sequences directly, with MobSketch they need only create new graphical elements, or drag existing elements around to update the plan; the actual commands are no longer the primary representation, the graphical elements function as a higher level programming language. Macros are re-applied anytime the graphical plan changes, thus the sequence of commands is automatically kept up to date with the graphical MobSketch plan.

The sequencing infrastructure used by the macros was updated in support of Rapid Traverse. Instead of assuming that a drive would only be commanded during a single boot cycle on a single sol, sequences were updated to label and track each portion of a multiple-sol drive separately. The label for the current drive leg would now be stored in a non-volatile sequence variable, so that a given drive plan could be restarted any number of times, easily picking up wherever the last drive left off.

Downloading Imagery Used for Onboard Autonomy

The inclusion of the VCE for faster image processing while driving with Visual Odometry and/or Autonav is a significant change from past rover missions. This enables the rover to drive greater distances in these modes during the available drive time, and as a result, many more stereo images are acquired over the course of a drive, roughly one stereo pair per meter driven. A 200 meter drive produces over 250 megabytes of image data. These onboard stereo images are saved into non-volatile flash storage on the VCE in a ring buffer, but will only be sent back to Earth if operators command them to be migrated to the RCE and saved in data products. Since this image data is typically only used for engineering analysis and does not directly support the mission's science objectives, we do not request all of these images to be returned to Earth. The Mobility team has instead developed a strategy for selecting which images should be retrieved to enable longer term analysis and trending without exceeding data volume limits:

1. In certain fault cases, the last few images pairs from a faulted drive will be retrieved automatically for downlink at a high priority to provide visual context for what terrain was being traversed when the fault occurred.
2. Image pairs are usually sampled for every 5th pair

throughout a drive, approximately one pair for every 5 meters of driving. This provides visibility of most of the terrain that was traversed and enables recreating height maps on the ground to assess mapping performance. On sol 395 we temporarily switched to sampling every 7th pair for the rest of Rapid Traverse due to onboard data product storage limits on the rover, as the substantial amount of driving during Rapid Traverse generated significantly more data than could be downlinked in a timely manner.

3. The last five images pairs are retrieved from the end of most drives, often providing important context of what the terrain looks like underneath the rover at its final position. Consecutive image pairs also enable us to better assess Visual Odometry performance.
4. In any cases where a downlink operator observes unusual behavior or poor performance during a drive (e.g., unusual obstacle avoidance during autonomous driving or a low feature count for Visual Odometry), the relevant images may also be retrieved if they are still available in the ring buffer.

We hope that this collection of images will provide a rich data set for longer term performance trending and tuning of stereo and Visual Odometry software, future autonomous algorithm development, and also provide terrain context for future mobility studies.

Verification Updates

In addition to updated macros, our sequencing validation tools were also updated. The tool that calculates the duration of the drive was updated to account for the possibility of mid- or post-drive Attitude Updates, as well as the time needed to transfer VCE images to the RCE for downlink. (Transferring the entire 540 image ring buffer could take as long as one hour). With drive distances of over 200 meters being achieved routinely, resulting in over 400 images entering the VCE buffer, those images needed to be transferred prior to the next 200+ meter drive, or they would be automatically deleted.

The tool that validates all the planned command sequences was also updated to recognize the new Rapid Traverse patterns, to ensure that any multi-sol drive was implemented with consistent labels and other associated parameters, like those selecting Attitude Updates and image download options.

5. STRATEGIC ROUTE PLANNING

Well before the Rapid Traverse Campaign started driving, a Strategic Route was created and reviewed by RPs and Science team members. Strategic Route Planning (SRP) on M2020 is done using the Campaign Analysis Mapping & Planning (CAMP) software, a web-based mapping tool that allows flexible annotations to be drawn over terrain maps of Mars [17], [18]. Terrain imagery typically comes from cameras on orbiting satellites like the HiRISE instrument on the Mars Reconnaissance Orbiter, providing maps with a resolution typically between 30 and 60 cm/pixel. CAMP is similar in operation to the interface provided at a public outreach website [19].

A small team of RPs worked with the campaign science planners to identify the Rapid Traverse route, with a focus on expeditiously driving to the Delta front region. While the straight-line distance between the start (sol 379) and end (sol 409) of Rapid Traverse was only 2.4 km, the most efficient and lowest risk route ended up being 4.8 km (Table 4). This longer route was safer because there were fewer traversability hazards along it – fewer rocky outcrops and sand features for the rover to cross. It was also a more efficient route because the onboard autonomous driving had already proven itself capable of traversing the long route's terrain, while the straight-line route (or any sort of variant of the direct route) would have had to navigate through Seitah, a region of complex topography, rocky outcrops, and many sand features.

M2020 Autonav relies on imagery from the mast-mounted Navigation Cameras (NavCam) to provide adequate 3D knowledge of the terrain, and sand features can sometimes result in gaps in the onboard stereo processing results that can perturb or prevent the algorithm's progress. To keep the vehicle safe in an uncertain environment, M2020 Autonav's hazard assessment calculations are conservative. In complex terrain with dense rocks, frequent rocky outcrops or gaps in coverage, this conservatism reduces the path efficiency and can prevent Autonav from making progress. Seitah is full of this type of complex terrain, so Autonav would not have been as effective. When evaluating the route options and predicting the drive rates along each, the strategic route planning team determined that traversing the 4.8 km route at peak Autonav rates (200-250 m/sol) would be far faster overall than traversing a shorter 2.4 km route with many sols yielding less than 50 meters of drive progress.

Figure 1 shows the final Rapid Traverse strategic route in CAMP. The blue route was the originally planned strategic route, and the green route is a version refined to account for better understanding of the terrain and vehicle performance.

Although in general the Science team avoided requesting observations that could slow the drive, they did identify a small number of scientific observations in advance and these were assessed strategically to quantify how much drive time (and how many campaign sols) they would cost. These fell into two categories: (1) mid-drive observations, where remote science (imaging) was acquired at a specific waypoint along the nominal drive path, and (2) route divergence to support Radar Imager for Mars' Subsurface Experiment (RIMFAX) measurements of specific terrain.

For mid-drive observations, the RPs construct the drive sequence of commands such that the rover will pause at a mid-drive waypoint to perform the science imaging. These observations typically include NavCam and Mastcam-Z images [20]. While a mid-drive observation does not cause the rover to deviate from the strategic route, it does take time away from the drive, so there is a trade-off.

There was only one route divergence made to support RIMFAX, a ground-penetrating radar instrument mounted under the rover. The RIMFAX observation drive can be seen in Figure 1 as the green L-shaped segment about half way through Rapid Traverse. This route deviation enabled RIMFAX to scan the transitional terrain and subterranean geologic features on the northern rim of Seitah.

6. TACTICAL DRIVE PLANNING

Unlike during normal mission operations, no arm-based plans were even considered during the Rapid Traverse Campaign. Every day was a new opportunity to make further progress along the strategic route toward the Delta at the rim of Jezero crater.

Table 4. Results from the 27 planned Rapid Traverse drives. The planned drives on sols 381, 391, and 392 were not executed.

Sol	Drive #	PlanType	Mobility Sequence Duration	Limited By	Driven Odom	Route Progress	Total Odom	Total Progress
379	1	Single sol	2hr 54min	Decisional comm pass	205m	179m	205m	179m
380	2	Multisol 1/2	3hr 56min	Non-decisional comm	259m	243m	464m	422m
381		Multisol 2/2	4hr 15min	Decisional comm pass				
382	3	Single sol	3hr 59min	VO-Sun elevation cutoff	298m	288m	762m	710m
383	4	Multisol 1/3	3hr 26min	VO-Sun elevation cutoff	241m	228m	1,003m	938m
384	5	Multisol 2/3	3hr 8min	Non-decisional comm	215m	195m	1,218m	1,133m
385	6	Multisol 3/3	2hr 10min	complex Terrain / RP eval	14m	13m	1,232m	1,146m
386	7	Single sol	3hr 25min	VO-Sun elevation cutoff	245m	236m	1,477m	1,382m
387	8	Single sol	3hr 32min	VO-Sun elevation cutoff	264m	233m	1,741m	1,615m
388	9	Single sol	3hr 38min	VO-Sun elevation cutoff	257m	249m	1,998m	1,864m
389	10	Single sol	3hr 15min	Non-decisional comm	244m	234m	2,242m	2,098m
390	11	Multisol 1/3	3hr 12min	Non-decisional comm	127m	128m	2,369m	2,226m
391		Multisol 2/3	3hr 18min	Non-decisional comm				
392		Multisol 3/3	2hr 15min	RIMFAX observation				
395	12	Single sol	2hr 50min	Decisional comm pass	202m	197m	2,571m	2,423m
396	13	Single sol	2hr 14min	Decisional comm pass	162m	158m	2,733m	2,581m
397	14	Multisol 1/3	1hr 25min	SuperCam/Mastcam-Z	68m	61m	2,801m	2,642m
398	15	Multisol 2/3	3hr 22min	VO-Sun elevation cutoff	235m	162m	3,036m	2,804m
399	16	Multisol 3/3	3hr 0min	Decisional comm pass	218m	214m	3,254m	3,018m
400	17	Single sol	2hr 56min	Decisional comm pass	216m	206m	3,470m	3,224m
401	18	Single sol	2hr 36min	Decisional comm pass	184m	181m	3,654m	3,405m
402	19	Single sol	2hr 44min	Non-decisional comm	183m	175m	3,837m	3,580m
404	20	Multisol 1/2	3hr 43min	VO-Sun elevation cutoff	260m	278m	4,097m	3,858m
405	21	Multisol 2/2	3hr 32min	Non-decisional comm	268m	281m	4,365m	4,139m
407	22	Single sol	2hr 51min	Non-decisional comm	209m	206m	4,574m	4,345m
408	23	Opportunistic Ext.	3hr 41min	VO-Sun elevation cutoff	274m	269m	4,848m	4,614m
409	24	Opportunistic Ext.	3hr 19min	Non-decisional comm	217m	209m	5,065m	4,823m

When can we drive?

The amount of time available for driving on any given sol is constrained by several factors.

Sun in FOV The NavCams used for autonomous image processing are susceptible to artifacts created when the Sun is inside their field of view (FOV). They have a wide FOV, 75°vertically and 90°horizontally, so we generally limit our driving to times when the Sun is high enough in the sky not to enter the FOV. In practice, this varies with the seasons, but generally means not too early in the morning and not too late in the afternoon.

Thermal Wheel motors, cameras and other subsystems must be operated within their nominal temperature range, which means they must either be pre-heated (requiring power and time), or activities must wait until the ambient temperature is sufficiently high. This generally constrains us to start drives relatively late in the morning.

Communication Communication passes with Earth or with orbiting relays generally require the rover to be stopped. So either driving activities must cease during a comm pass, or passes scheduled during driving must be deleted. During Rapid Traverse, we often chose to delete mid-day comm passes to enable longer drives.

The net effect of these constraints is apparent in Table 4, which shows that we were never able to plan for more than 4.25 hours of actual driving on any single sol.

Where can we drive?

The overall path to the Delta (shown in Figure 1) was determined well in advance of the Rapid Traverse Campaign. RPs on shift for a given planning day do have the authority to override a strategically chosen route if necessary for vehicle safety or to accomplish additional goals. But during this campaign, no additional goals were allowed, and Tactical RPs were planning the drive in the same orbital terrains used to generate the strategic plan. So in nearly every case, the Tactical team followed the strategically laid-out route quite closely.

How should we drive?

Whenever planning from a known starting state, RPs will typically start the day with a human-guided Directed drive for up to 30 meters distance from the starting point. But since Rapid Traverse had a constant need to drive as far as possible, most of the drive plan needed to be planned as Autonav drives by necessity. The strategic route was chosen to maximize the use of Autonav, and the results demonstrate that RPs were in fact able to use Autonav extensively. There had been

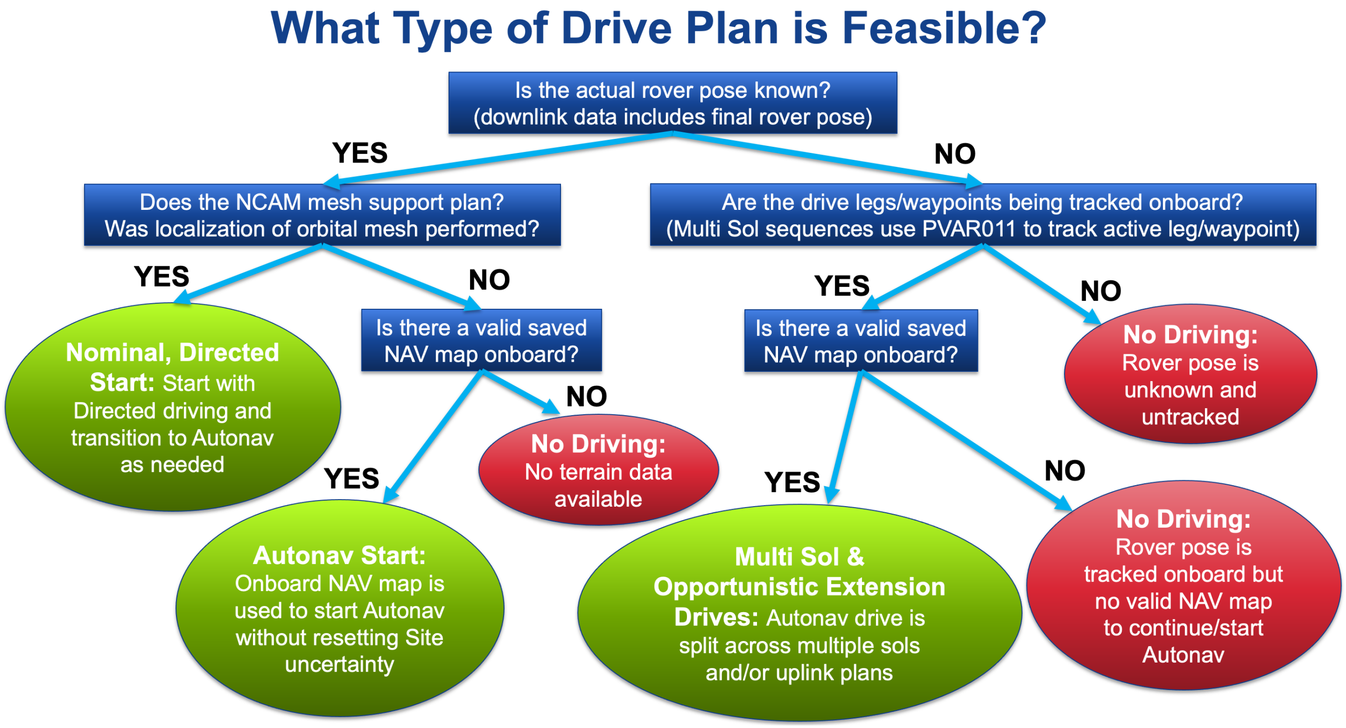


Figure 2. Chart illustrating the process used to determine what drive strategies are available on any given planning sol.

some concern about a small number of sand ripples near the preferred path, but operationally they proved to be no trouble for the Autonav system, which either chose to avoid them due to missing (occluded) data, or happily drove over them while incurring insignifact amounts of wheel slip.

7. DRIVING STRATEGIES USED DURING RAPID TRAVERSE

During Rapid Traverse, several types of drive plans were used to most efficiently complete the route. These are illustrated in Figure 2.

The simplest drive plan type is a single-sol drive. To plan a single-sol drive, the Tactical Operations team needs to have received the latest NavCam imagery of the terrain around the rover. Since these images are taken from the rover's final position after the most recent drive, they provide the most reliable view of the nearby terrain and do not require localization corrections. Single-sol drive plans typically start with a short **Directed drive** portion, where the RPs choose the path the rover will drive and use a 3D mesh constructed from the NavCams to identify hazards and simulate terrain interactions.

After the Directed portion, **Autonav** is turned on and the RPs set mid-drive waypoints approximately every 120 meters (or shorter) along the strategic route. When Autonav is enabled, Perseverance automatically identifies and avoids hazards in realtime, so NavCam images of the terrain are not required for human assessment. At the end of a single-sol drive plan, Perseverance sends data back to Earth, including the driven path, final position, post-drive NavCam imagery, and more. This data enables the Operations team to schedule more Directed driving in the next sol's plan.

The M2020 Operations team now plans operations on a 5 days per week cadence, so Friday is typically a multi-sol plan, spanning three sols on Mars to cover the weekend. To plan a drive that spans multiple sols, the RPs sketch a route that has enough distance to keep the rover busy for all the sols in the plan. For example, a weekend plan with over 6 hours of time for driving might warrant a route longer than 1 km. To guide the rover along long routes, RPs set mid-drive waypoints about 120 meters apart to separate the drive into straight-line segments, or legs. Once per leg, the rover can choose to autonomously perform a mid-drive SunID update to eliminate heading knowledge uncertainty that accrues over time. While the first sol of a multi-sol plan may have a local NavCam mesh to support human hazard evaluation and Directed driving, later sols will rely entirely on Autonav to avoid hazards.

The rover will drive as far as its allocated time allows on each sol of a multi-sol plan, so the starting position for the second sol and beyond is unknown. To overcome this uncertainty, the rover tracks which drive leg it is currently executing using persistent variables (PVARs). These floating-point variables persist across boot cycles and can be set to arbitrary values via spacecraft commands. Basic addition and subtraction as well as conditional checks can be performed on PVARs in command sequences; this allows subsequent sol plans to continue a drive at a variable drive leg indicated by the PVAR value. This strategy allows the RP to construct one continuous drive sequence with many drive legs and enables the rover to start and stop along that route an arbitrary number of times.

These PVARs also enable a new type of driving designed for Mars 2020 – **Opportunistic Extension drive** plans. For this type of drive plan, RPs construct a subsequent drive without knowing the actual starting location of the rover. This lack of initial conditions occurs frequently during Mars missions due to ”restricted” planning periods, where the execution of a plan during the Martian day does not complete early enough to provide data in time for the human operators to plan during daytime shifts on Earth. Typically, this lack of final rover state data from the previous sol would prevent drive planning, but during Rapid Traverse the team developed a strategy to use the onboard PVARs to ”extend” previously planned drives. When creating an extension drive sequence, the RPs start with the exact same commands that were previously sent to the rover. The PVAR logic automatically restarts the drive at the same segment in which it stopped, preventing earlier, already-completed drive legs from being re-commanded. The RPs then add additional waypoints to extend the drive beyond what was previously planned. This strategy allows extending drive plans arbitrarily across restricted planning periods, with humans never needing to know where one drive ends and the next drive begins.

The benefit of Opportunistic Extension drives is that rover operations can be almost twice as efficient during restricted planning periods. Consider a long period of restricted planning sols. If human operators require final rover state data to command drives, then at most the team can command a drive every other day, and a whole sol of progress on Mars would be lost in between single-sol drives. Using Opportunistic Extensions, RPs are able to add additional drive distance to the plan every day they’re on shift, spreading out the workload and continually feeding the rover new activities. While a similar drive cadence could be achieved using multi-sol drives and releasing human operators from restricted shifts, the team is able to react faster to anomalies if they are staffed every day, and Opportunistic Extension drives help maintain efficiency during these restricted communication periods.

The limiting factor for Opportunistic Extension drives is the continuing growth of onboard global localization uncertainty. Perseverance currently does not have an onboard capability to localize itself against an orbital map, so its position estimate relative to hazards identified by the RPs using orbital terrain maps becomes less trustworthy as it drives. After several sols of extension drives, the uncertainty in position has grown large enough to hinder safe navigation, and the operations team on Earth must pause driving to manually re-localize the rover in the orbital maps using local NavCam images. Every such re-localization allows the onboard uncertainty to be reset to zero.

The sol 407-409 drives were implemented as Opportunistic Extensions. Figure 3 shows all drives planned for sols 407–409, illustrated in the MobSketch tool RPs use for nominal mobility planning. At this time during Rapid Traverse, the operator shift times on Earth and rover execution times on Mars were not well-aligned, so data from the prior drive was not available until Earth-evening. To overcome the lack of data during the daytime planning shift, RPs had to create a plan that would work no matter where the rover was; it could be anywhere along the previous sol’s plan, at the final goal, at the start line, even far off the nominal path if it had found geometric hazards and tried to avoid them. This turned out to be a record-setting drive, achieving over 699 meters during the three sols of driving, with humans never knowing exactly what had happened on the previous sol when planning the current sol.

8. MOBILITY DOWNLINK ASSESSMENT

The Mobility Downlink team is responsible for monitoring and assessing the health, safety, and performance of the rover’s mobility subsystem based on the available telemetry. Telemetry consists of “Event Reports” (EVRs), “Engineering, Housekeeping, and Accountability” (EH&A) channelized telemetry, and timestamped binary files called “Data Products”. These are similar to the telemetry generated by the MSL and MER rovers [21]. Images, parameter dumps, high-rate telemetry, and Autonav height and cost maps are just some examples of the types of data that may be packed into data products.

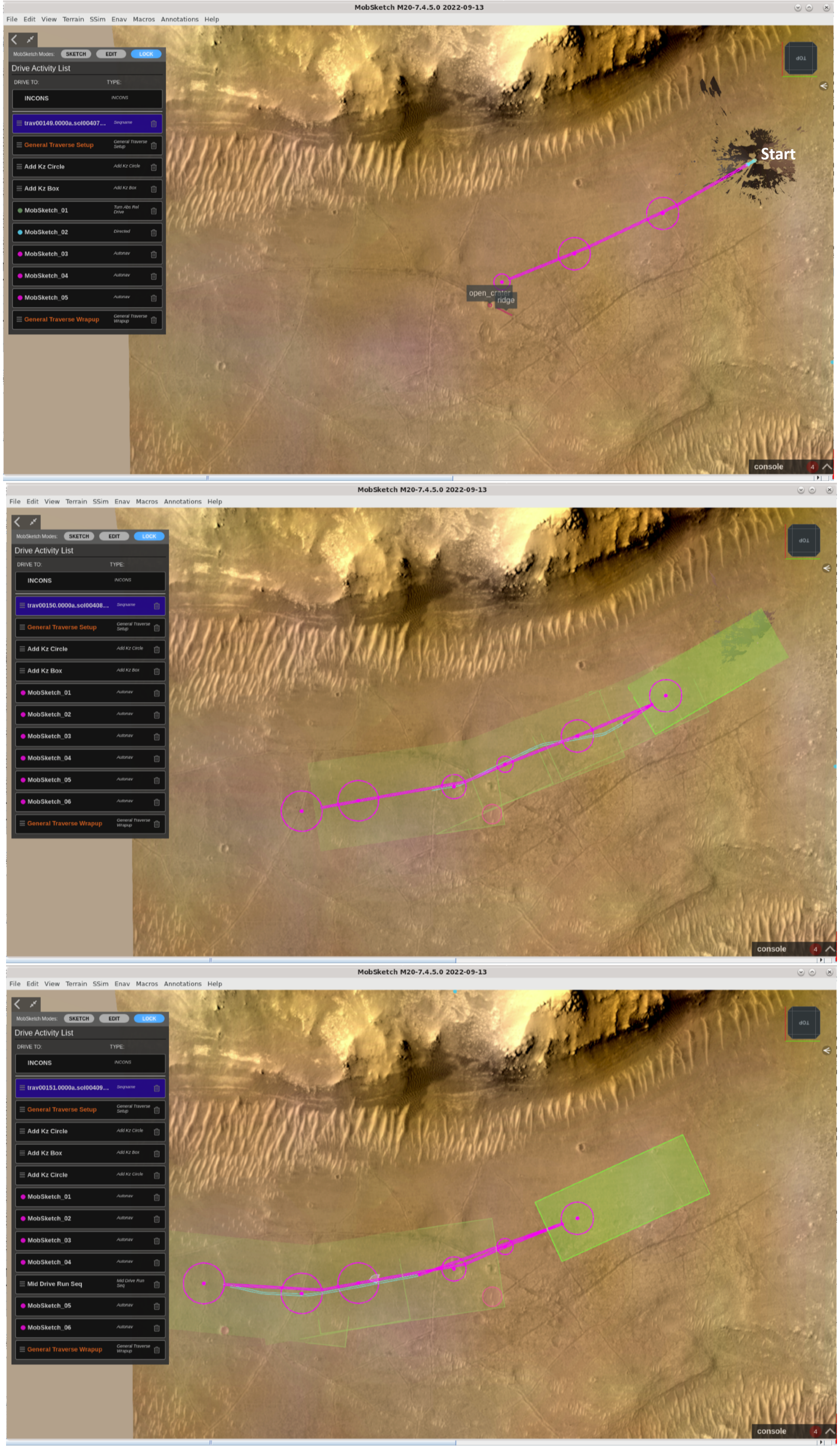
At the start of every planning shift, a Mobility Downlink analyst is responsible for reviewing any new data relating to the mobility subsystem to determine if the vehicle is performing as expected and giving a “Go” or “No-Go” decision indicating whether it is safe to continue driving. In most cases, this assessment involves reviewing any driving that was planned and uplinked to the rover during the prior operations shift. One notable exception for mobility is Opportunistic Extension driving. In that case, the most recent drive data might not be available yet, and so Mobility Downlink must assess an even earlier drive and consider whether the end state of the earlier drive may impact the anticipated performance of the more recently planned drive.

Since downlink communications are data volume limited, we might not necessarily receive all data from the latest drive in time for the next planning shift, so data must be prioritized. Most EVRs and EH&A are at a ”critical” (very high) priority and provide context for the activities that executed and whether or not there were any faults encountered. PDI is also at a critical priority and typically includes front and rear Hazard Camera (HazCam) stereo pairs showing terrain under the front and rear wheels as well as a mosaic of NavCam stereo pairs covering the direction we are most likely to drive next. Any data products that include anomaly reports are also at a critical priority to ensure we have high-rate data and other context around the time of a fault so we can more quickly assess the cause of the fault.

High-priority mobility data products are usually received in time for the next planning shift. They include motion history products which contain high-rate data throughout the whole drive and a height map product created at the end of any Autonav drive showing the rover’s onboard model of the shape of the terrain around and under the vehicle. Medium-priority mobility data products are less likely to be received in time for the next planning shift. They include more details about the path choices that Autonav made as well as the final cost map which shows which regions Autonav decided were high cost and why. VCE images, which include NavCam stereo pairs used for Visual Odometry computations and Autonav map building, may be requested at different priorities, but most VCE images are selected for downlink after the drive that generated them and are assigned the lowest priority.

The first priority during a downlink assessment is to understand the final state of the vehicle. Answering the following questions is usually sufficient to determine if mobility is ”Go” to continue driving on the next sol.

- Were there any faults that stopped the drive early or warning messages indicating potential issues during the drive?
- Is the vehicle stable with all wheels on the ground?
- Are there any hazards visible near or under the vehicle in



DRIVE TO:	TYPE:
INCONS	INCONS
trav00149.0000a.sol00407…	Seqname
General Traverse Setup	General Traverse Setup
Add Kz Circle	Add Kz Circle
Add Kz Box	Add Kz Box
MobSketch_01	Turn Abs Rel Drive
MobSketch_02	Directed
MobSketch_03	Autonav
MobSketch_04	Autonav
MobSketch_05	Autonav
General Traverse Wrapup	General Traverse Wrapup

DRIVE TO:	TYPE:
INCONS	INCONS
trav00150.0000a.sol00408…	Seqname
General Traverse Setup	General Traverse Setup
Add Kz Circle	Add Kz Circle
Add Kz Box	Add Kz Box
MobSketch_01	Autonav
MobSketch_02	Autonav
MobSketch_03	Autonav
MobSketch_04	Autonav
MobSketch_05	Autonav
MobSketch_06	Autonav
General Traverse Wrapup	General Traverse Wrapup

DRIVE TO:	TYPE:
INCONS	INCONS
trav00151.0000a.sol00409…	Seqname
General Traverse Setup	General Traverse Setup
Add Kz Circle	Add Kz Circle
Add Kz Box	Add Kz Box
Add Kz Circle	Add Kz Circle
MobSketch_01	Autonav
MobSketch_02	Autonav
MobSketch_03	Autonav
MobSketch_04	Autonav
Mid Drive Run Seq	Mid Drive Run Seq
MobSketch_05	Autonav
MobSketch_06	Autonav
General Traverse Wrapup	General Traverse Wrapup

Figure 3. View of the planned Opportunistic Extension drive planned for sols 407–409, as visualized in the MobSketch tool. Sol 407 is on top, 408 in the middle, 409 on the bottom. The cyan line in the top image is a directed drive leg, the magenta lines are Autonav drive legs, the green lines are the simulated drive, green boxes are keep-in zones, the red circle in the middle and bottom image are a keep-out zone, and the magenta circles are waypoint tolerances. All the goals from the preceding sol's drive must also be included in the plan since the actual rover position is not known.

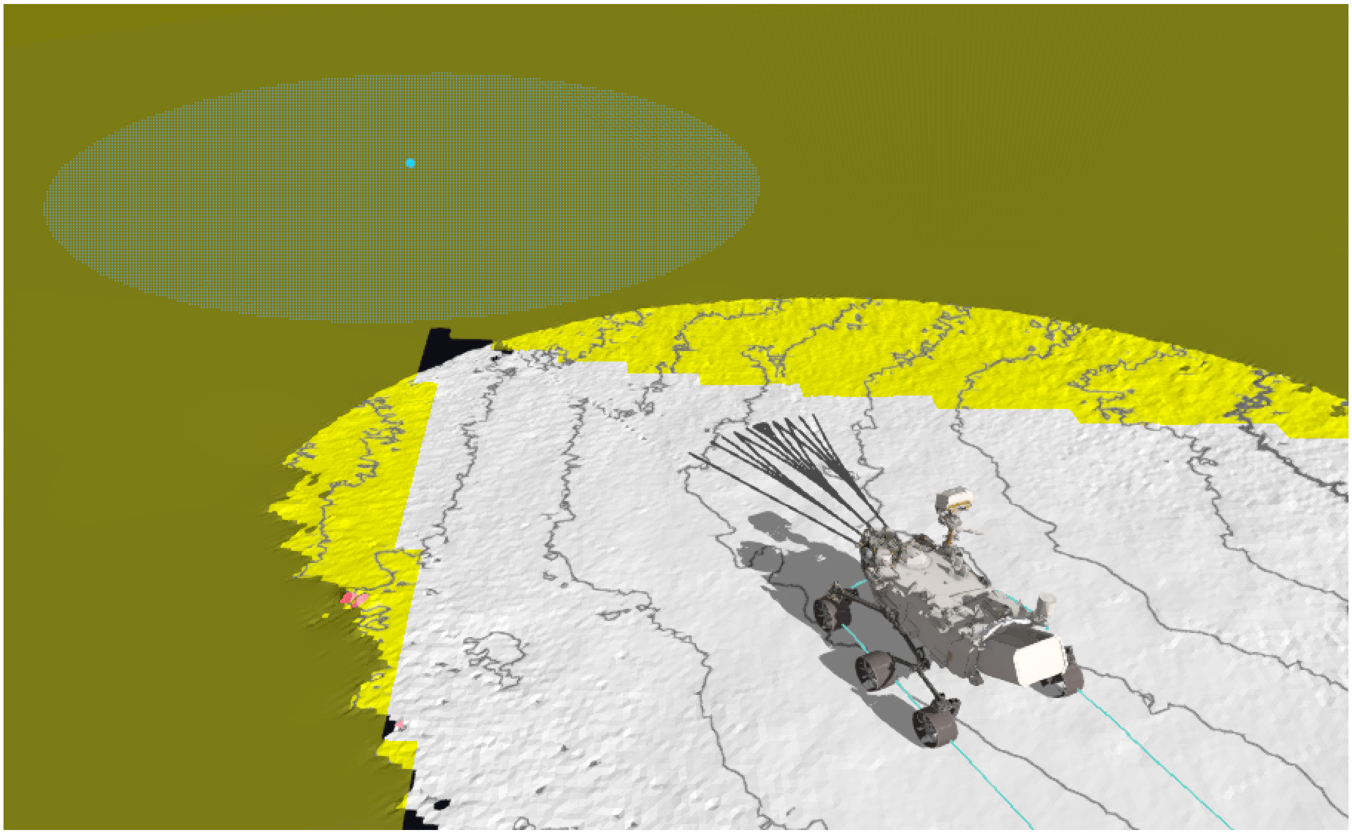


Figure 4. Visualization of Autonav data in the Caspian tool showing the end of the sol 385 drive that faulted due to no path to the goal. Cyan circle is the current drive goal. A height map shows the shape of the terrain under and near the rover. Yellow highlights regions from the larger cost map where the rover is not permitted to drive because it may get too close to operator defined keep out zones.

any of the post-drive images?

- For Autonav driving, are there any unusual features detected in the final height map near or under the vehicle?

The second priority is to assess performance over the course of the drive.

- Were there any locations where Visual Odometry had poor performance?
- Did Autonav divert around any possible hazards or make any unusual choices for the drive path?
- Were there any areas of high wheel slip?
- Was the motor telemetry consistent with what we typically observe during nominal driving?

Further data inspection in cases where some unusual behavior occurred may provide insight into changes that should be considered for future drives, for example, changing parameters that impact behavior or planning drive routes that avoid terrains where we expect poor performance. Prioritizing the assessments in this way is especially important during very long drives since 1) the more detailed data may take longer to fully review and might not all be received in time for the current planning shift, and 2) poor performance in the middle of a long drive generally does not indicate any significant concerns for the next drive if that prior drive ended nominally.

There was only one situation during the Rapid Traverse Campaign that a ”No-Go” decision was given for mobility. On sol 390, a previously unknown bug caused the flight software to reset in the middle of a drive and go into standby mode. Since the reset prevented some onboard state information from being saved to the rover's nonvolatile memory, additional commanding was required to recover the onboard state prior to driving again.

All but one of the other drives during Rapid Traverse executed until they reached the end of the time allowed for driving, as shown in Table 4. Drive time may be limited during planning by the timing of communication passes, heating constraints, and sun elevation requirements for Visual Odometry. The sol 385 drive stopped early due to Autonav determining that there was no safe path to the goal. This occurred during the third sol of a three-sol weekend plan with drives every sol, and this outcome was anticipated by the uplink team. The desired drive path involved navigating a small corridor between two crater rims which were blocked off by ”keep out zones” to prevent the rover from wandering down into a crater.

After 469.786 meters of driving during the plan, the rover's estimate of position uncertainty had grown so large that it could not find a path that would guarantee that it would not enter either of these zones, so it stopped. In this case, the Mobility Downlink analyst was able to view the cost map in the Caspian tool (screenshot in Figure 4) to see that regions reserved for ”keep out zones” were entirely blocking the route toward the goal, as predicted by the uplink team. With new images from this position, the RPs could reset the position uncertainty and verify the locations of the crater rims, enabling the rover to safely drive between them and continue along the Rapid Traverse route.

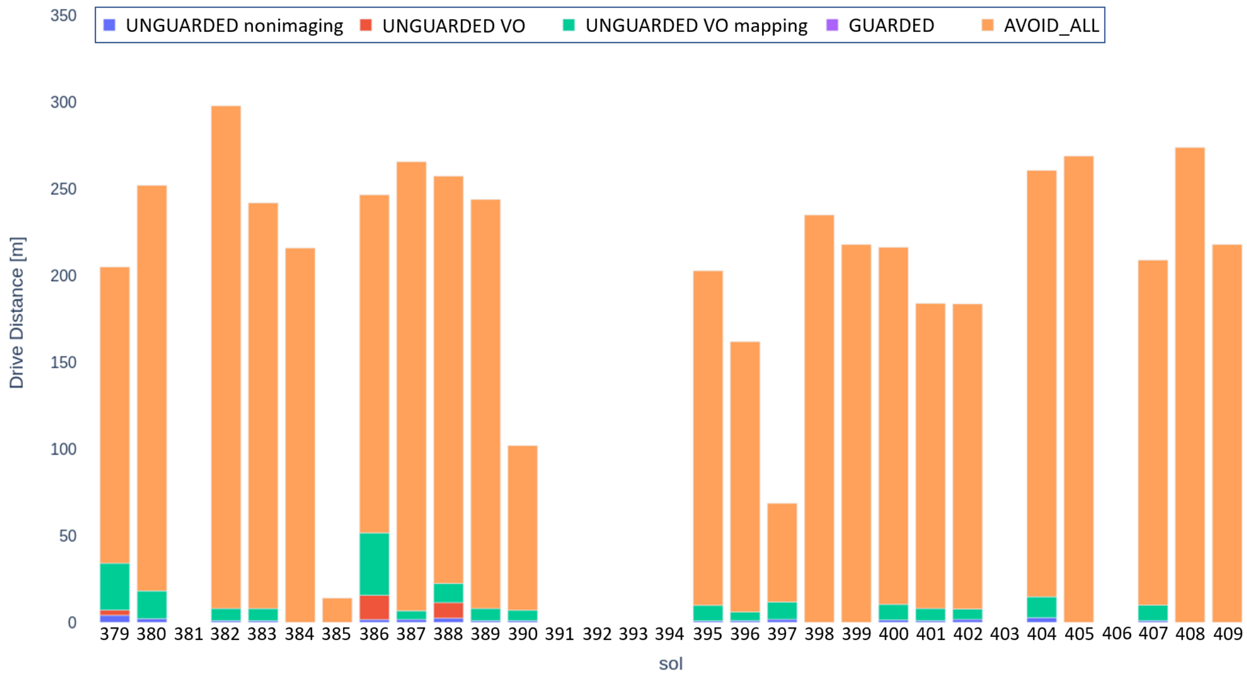


Figure 5. Odometry per sol during the Rapid Traverse Campaign, from sol 379 through sol 409. This highlights the drive distances in Table 4 and just the Rapid Traverse data from Figure 6.

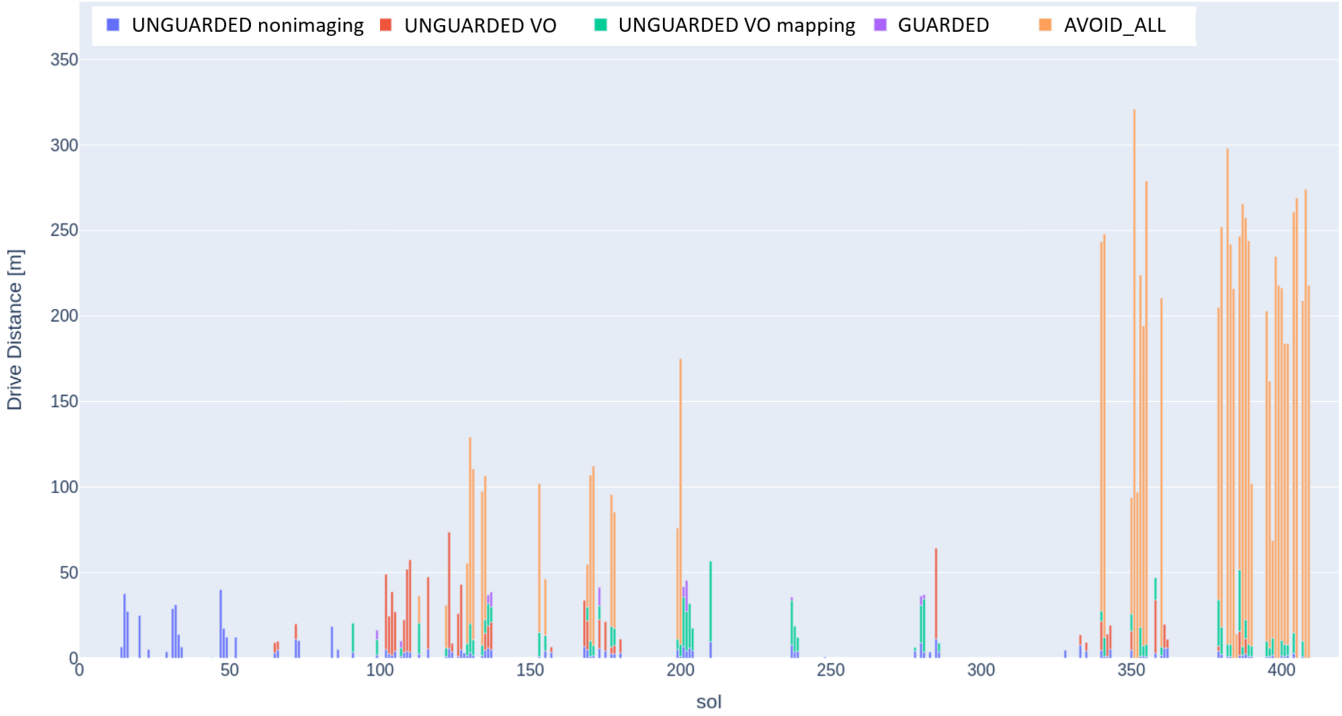


Figure 6. Odometry per sol from the beginning of the mission to the end of the Rapid Traverse Campaign.

Opportunistic Extension driving was planned for the first time during sols 407 to 409. A drive was planned on sol 407 following standard practice. During sol 408 planning, no data had been received yet from the sol 407 drive, but additional Autonav driving was commanded with additional waypoints added to the sol 407 drive path to extend it. During sol 409 planning, data had been received from the sol 407 drive but not the sol 408 drive (as expected). In this case, Mobility Downlink could only assess the sol 407 drive to confirm that drive performed as expected. Knowing the vehicle state from sol 407, the team could then predict that the previously planned sol 408 could proceed nominally. The team then decided to further extend this drive on sol 409 with an additional waypoint that would reach the Delta site.

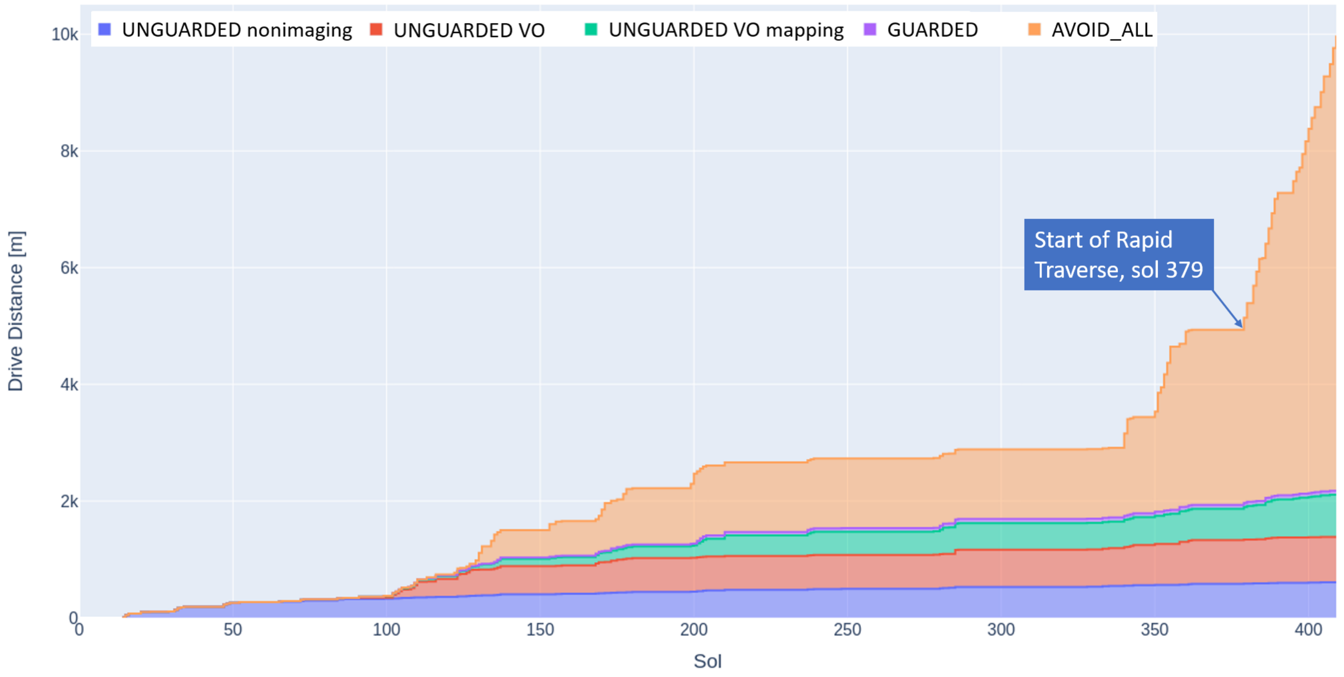


Figure 7. Cumulative odometry per drive mode from the beginning of the mission to the end of the Rapid Traverse Campaign.

9. CAMPAIGN RESULTS

The Rapid Traverse Campaign spanned 31 sols, starting on sol 379 and ending on sol 409. Over the 31 planning sols, drives were planned on 27 sols. Twenty four of the planned 27 drives executed on Mars, resulting in 5,063.4 meters of odometry, of which 4,802 meters (94.8%) was from Autonav.

Figure 5 highlights the drive distance accomplished in each drive mode for each drive sol during the 31-sol Rapid Traverse period. Figure 6 illustrates the high frequency of long-distance Autonav driving that occurred during Rapid Traverse relative to the rest of the mission. Figure 7 illustrates how the cumulative odometry accrued during the one month Rapid Traverse Campaign exceeded the total odometry achieved prior to it, and nearly all of Perseverance's driving during Rapid Traverse was in Autonav mode.

One of the Rapid Traverse drives ended early (on sol 390) due to a flight software unexpected reboot (FSW ”fatal”) that caused Perseverance to enter safe mode. The FSW fatal occurred on the first sol of a three-sol weekend plan, and as a result of the fatal, further mobility was precluded, preventing the sol 391 and 392 drives from occurring. The sol 393 plan focused on recovery from the sol 390 FSW fatal and the sol 394 plan captured PDI needed to plan the next drive.

Table 4 contains the results from the 27 planned drives. The predominant factors that limited drive durations were completing a drive before a non-decisional orbiter communications window, completing a drive before a decisional orbiter communications window, and completing a drive before the sun was low enough in the sky to potentially cause artifacts in onboard driving maps.

Table 5 lists the reasons why there was no drive on 7 of the 31 sols during Rapid Traverse. Driving did not occur on one sol because the plan was pulled due to an issue with a ground tool used to simulate sequences, on four sols due to the sol 390 FSW fatal and its recovery, and on two restricted sols (days on which data from Mars arrives too late on Earth to be useful for planning).

Table 5. Reasons why a drive did not occur on seven sols during Rapid Traverse.

Sol	Reason why there was no drive on this sol
381	Planned drive pulled due to a ground tool issue
391	Planned drive precluded due to sol 390 FSW fatal
392	Planned drive precluded due to sol 390 FSW fatal
393	Recovery from sol 390 FSW fatal
394	New images acquired for planning the next drive
403	Restricted sol
406	Restricted sol

The modeled total duration of the mobility sequences in the 27 planned drives was 80.35 hr, with a modeled average duration of 2.98 hr/sol. The average drive rate during Rapid Traverse was 79.7 m/hr. The average non driving mobility sequence duration was 27.7 min per drive sol, which included setup, wrapup, mid-drive SunIDs, and VCE image retrievals.

In March 2005 (MER sol 410), Opportunity drove 219 meters, setting a record for the longest drive in a single sol by a planetary rover. That record was held for nearly 17 years by Opportunity until Perseverance drove 319.786 meters on February 15, 2022 (sol 351), 28 sols before the start of Rapid Traverse. Although Perseverance did not surpass the single sol distance record during Rapid Traverse, several other records were set.

On sol 399, a new record was set for the most odometry driven in a single plan: 520.499 meters was driven in the sol 397-399 three-sol plan. On sol 409, a new record was set for the most continuous odometry driven without ground-in-the-loop. 699.851 meters was driven over sols 407-409 using Opportunistic Extention plans. It is also noteworthy that 11 of the 24 Rapid Traverse sols resulted in single-sol drives longer than 219 m, thus exceeding all previous rovers' single-sol drive distances.

10. LESSONS LEARNED

Here are some of the lessons that were learned during of the Rapid Traverse Campaign:

Rapid Traverse provides a model of an effective campaign

Campaigns that achieve unprecedented results set a clear priority and focus the entire team on a common goal. Reasons inevitably come up for deviating from the goal and making allowances for other priorities. For each of these, the model the M2020 team adopted was to ask whether they would reduce drive progress, not just in the short term, but over the entire campaign, and used that to filter requests. The daily Tactical and Campaign Implementation planning teams did well by requiring non-drive requests to be reviewed strategically, days in advance, so that more driving could be accomplished.

Strategic planning that provides usable guidance for day-to-day planning is effective in ensuring daily decisions are synchronized with the campaign strategy

The M2020 SRP team created a robust 5 km drive plan weeks in advance of Rapid Traverse. The SRP team iterated on this plan with other teams on the project, ensuring it met the science goals and took into account resource constraints specific to the targeted dates such as communication passes, seasonal temperature, and data storage. The SRP was available in rover planning tools as an annotated visual path. It simplified planning by always providing clear guidance even for multi-sol plans.

Plan for operations infrastructure to be stressed by campaigns that target the limit of capability day after day, and have backup plans

It turned out all the team efforts to maximize driving on Mars led to stressing both the ground and flight system. Even though the team had completed drives and multi-sol driving already prior to the campaign, early in the campaign, a ground tool broke due to too many EVRs and drive calls being initiated in our modeled products, causing a file size limit in the ground tool to be exceeded. The team recovered by using a manual workaround where the tool did not model every single drive command during the drive sequence.

Monitor resource constraints, maintain margin in the early stages of the campaign, and have fallback plans for reducing usage

Total onboard storage on the rover became a concern and the team had to scale back on science data collection and engineering imaging to help reduce the backlog of data. Much of team thought we would collect less data overall during this period because there was limited science, but as it turned out all the engineering imagery we collect during driving and higher resolution imaging being acquired created a backlog of data on the rover that the team quickly needed to address by adjusting plans to acquire less data and enable more compression of certain data products.

Expect surprises and plan for agile tool development and deployment

Tool and macro updates were quite helpful, especially the rapid fixes to unforeseen problems that arose during tactical planning. Some tool updates were inevitable, given the fact that we had changed our operations models for this Rapid Traverse activity.

Armed with analysis and risk mitigations, don't be afraid to add new capability that may have a high reward

This was the first period during which we attempted to drive autonomously around and through small sand ripples, and that behavior worked well. It allowed a more direct route through regions of small ripples increasing the rate of progress to the campaign destinations.

Opportunistic Extension drives are useful for limiting plan complexity

For this type of drive plan, RPs construct a subsequent drive without knowing the actual starting location of the rover. Opportunistic Extension drives can be used on restricted planning days. A similar drive cadence could be achieved using multi-sol drives and releasing RPs on restricted planning sols. However, Opportunistic Extension driving allows plans to be shorter in length (i.e., less complex) while still achieving the same drive efficiency. In addition, the team can react to anomalies faster during drive campaigns if they are staffed on restricted planning days.

Document lessons learned to get even better results with the next campaign

Several compromises were made that resulted in less actual driving time. We had previously exercised the ability to start heating mobility motors "early" in the morning and have Autonav hand control over from one sol's main sequence to the next, to allow drives to start earlier in the day. But this capability was temporarily prohibited, to eliminate the complexity of creating such dependencies across sol plans. Also, activities such as mid-drive SunID updates and VCE image transfer activities each require multiple minutes to execute, but instead of running them in parallel, the team opted to run them serially in order to avoid the possibility of resource contention resulting in a fault. Several other candidates for parallel execution during the setup and wrapup periods of each drive were also kept serial for the duration of Rapid Traverse. While these decisions kept operations simple, they also limited the amount of driving that could be accomplished in a given sol, and will likely be revisited for any future long-drive campaigns.

11. CONCLUSIONS

The Rapid Traverse capability allowed the M2020 mission to quickly move from detailed science investigation in one distinct region of high science value to another, thus optimizing science return. Perseverance transported a significant payload (a sampling system capable of collecting and caching 43 sample tubes, a robotic arm, surface abrading and dust removal tools, and seven science instruments weighing 59 kg) over more than 5 km in a record-breaking duration.

Rapid Traverse was a very successful campaign that enabled Perseverance to reach Three Forks in 31 sols. It was unprecedented in both the total distance driven in a 31 sol period (5,063.4 meters) and the percentage of odometry performed using Autonav (94.8%). The total distance Perseverance drove during Rapid Traverse was 2.7 times that achieved by any previous planetary rover during a 31 sol period.

Rapid Traverse validated the strategic planning process and fidelity of operations tools in predicting the drive schedule for a dedicated drive campaign. Prior to the start of the Rapid Traverse campaign, the M2020 SRP team forecasted that the Three Forks area would be reached after 22 drives averaging 218 meters of progress per drive sol. In fact, Three Forks was reached within margin of that estimate (in 24 drives) and the realized average route progress per drive sol was 201 meters. Two factors explaining why the traverse took two drives longer than forecasted were the sol 390 drive ending early due an unexpected system reboot, and the project having decided to deviate from the strategic route on sol 398 to perform a RIMFAX experiment on the edge of the Seitah region.

The campaign also highlighted the value in strategic planning while allowing tactical agility. Extensive strategic planning provided clarity from high-level options such as what science could be included to the low-level details of which communication pass to delete. It allowed the tactical team to focus on decisions that could not be made ahead of time. At the same time, the M2020 operations tools allow a quick determination of whether the outcome on Mars deviated from expectation, and enable fast replanning, such as when the reboot occurred on sol 390 and the drive ended early.

Use of Risk-Informed Decision Making [22] was an effective approach for selecting among the various SRP options for getting from the start to the destination of the Rapid Traverse Campaign. There were high stakes with a diversity of stakeholders involved in the decision, it was complex, it had multiple attributes, and there was substantial uncertainty in the outcome of the decision alternatives. Identification of the two main alternatives, followed by SRP to analyze risk of each helped select the successful path. It helped determine that the risk of the shorter path was much higher due to complex sandy terrain that had potential to pose challenges for Autonav, whereas the longer route had few impediments to speedy progress with Autonav.

The campaign was an example of the combination of ground based and onboard capabilities that are necessary for successfully operating autonomous robots. For example, ground tools enabled RPs to mark regions Autonav should avoid, and onboard Autonav had the capability to account for the increasing uncertainty in the position of these regions as drive distance accumulated. In addition, ground tools could provide information about the potential for self-occlusions during upcoming communications passes, and onboard Autonav could search for an end of drive location that allowed safely performing a turn that would ensure unoccluded communication with Earth.

There is potential to even further optimize the time available for driving in a given sol. For example, by reducing the complexity of performing actuator heating over handover from one sol to another, it could be possible to start driving earlier in the day. This could be accomplished by performing some of the startup for a drive in parallel such that it occurs while actuators are still being heated, performing some of the shutdown in parallel, and optimizing the heating by using onboard activity planning so less margin is needed without compromising safety.

The Rapid Traverse Campaign was so successful that the M2020 mission expects to re-use the playbook in the future. After Perseverance creates an initial sample depot in the Delta region and completes the Delta campaign, we anticipate more Rapid Traverse campaigns to quickly travel between distant areas of critical science interest.

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BIOGRAPHY

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Tyler Del Sesto *received his M.S. degree in Mechanical Engineering from Carnegie Mellon University 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.*

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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 Robotic Operations Deputy Team Chief, and a member of the Rover Planner and Rover FSW development teams. He holds a Ph.D. in Computer Science from Carnegie Mellon University.*

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